17657

NATIONAL LIBRARY
OTTAWA

CANADA

BIBLIOTHÈQUE NATIONALE
OTTAWA

NAME OF AUTHOR....MILTON W. PETRUK.....

TITLE OF THESIS....THE INFRARED COMPUTER.....
....BASED OCULOMETER.....
.....

UNIVERSITY....UNIVERSITY OF ALBERTA...

DEGREE FOR WHICH THESIS WAS PRESENTED..DOCTOR OF PHILOSOPHY

YEAR THIS DEGREE GRANTED.....1973.....

Permission is hereby granted to THE NATIONAL LIBRARY OF CANADA to microfilm this thesis and to lend or sell copies of the film.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

(Signed)....

PERMANENT ADDRESS:

....10904 - 40A Ave
....Edmonton, Alberta
.....

DATED. October 11.....1973

NL-91 (10-68)

The University of Alberta

The Infrared Computer Based Oculometer

by

© Milton W. Petruk

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF DOCTOR OF PHILOSOPHY

IN

Testing and Measurement

DEPARTMENT OF EUDCATIONAL PSYCHOLOGY

EDMONTON, ALBERTA

FALL, 1973

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled The Infrared Computer Based Oculometer submitted by M. W. Petruk in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

. . . . . .
Supervisor

. . . . . .

. . . . . .

. . . . . .

. . . . . .
External Examiner

Date September 28, 1973

ABSTRACT

The major purpose of this research was to develop a method of measuring and recording eye movements of subjects during various learning tasks. It was required that the method developed for this purpose record simultaneously, as many oculographic characteristics as possible, relatively unobtrusively, with no mechanical attachments and with minimum of constraints placed on the subject. It was also required that the recording speed and sensitivity be sufficient to record all conjugate eye movements in a form readily accessible for computer analysis.

The infrared computer based oculometer system developed consisted of an infrared television camera interfaced with a small computer. The eye of the subject was illuminated with infrared light, and an image of the eye was projected to the face of the infrared television camera. The small computer was used to monitor the video signal coming from the infrared camera via a specially designed interface unit, and to derive and store once every thirtieth of a second, both the pupil dilation and the displacement of the corneal reflection from the pupil center. Analysis of this data to determine and plot eye pointing coordinates was carried out off line, using an IBM 360/67 computer. This study describes and documents the development of the infrared computer based oculometer system.

Operating characteristics of the infrared computer based oculometer are discussed in terms of possible sources of error and in terms of accuracy of the system.

The performance of the infrared computer based oculometer was tested using a small number of subjects viewing a variety of stimulus situations. Plots of observed eye movements in relation to the stimulus situations are presented in this study.

Finally, a number of recommendations for improving the infrared computer based oculometer system are presented. Also further studies of eye movement measurements are recommended to enable additional analysis of error components inherent in the measurements.

ACKNOWLEDGEMENT

I wish to express my appreciation to Dr. S. M. Hunka for the continued encouragement and assistance which made the completion of this project possible.

A special note of thanks goes to my children, Trevor and Linda, especially Linda, who spent many hours as a willing subject during the initial testing and adjustment of the oculometer system.

Finally, a note of thanks to my wife, Ruby, who offered continued support and encouragement throughout the duration of this project.

TABLE OF CONTENTS

CHAPTER		PAGE
I.	INTRODUCTION	1
	Summary	6
II.	REVIEW OF LITERATURE	8
	Introduction	8
	Methods of Oculography	9
	Subjective Method	9
	Mechanical Method	11
	Direct Optical Method	12
	Electro-oculography	13
	Electronic Measurement Methods	14
	The Infrared Computer Based Oculometer	15
	Types of Eye Movements	16
	Conjugate or Versional Movements	16
	Vergence	19
	Tremor	19
	Eye Movement Research	20
III.	DESCRIPTION OF THE COMPUTER BASED OCULOMETER SYSTEM	30
	Introduction	30
	The Eye	31
	The Infrared Image	32
	The Camera	37
	The Computer-Camera Interface Unit	40
	The Computer	45
	The Computer Hardware	45

CHAPTER PAGE

The Software 47

The Output 53

Proof of Performance 55

Measurement of Linear Displacement 56

Determining Centers of the Pupil and Corneal Reflection 57

Actual System Performance 65

Summary 77

IV. DESCRIPTION OF TESTING AND PRESENTATION OF FINDINGS . . . 78

Introduction 78

Procedure 78

Analysis 84

Stimulus Situation 1 - Calibration 84

Conclusions 88

Stimulus Situations 2 - 4 100

Stimulus Situation 5 - Calibration Check 126

V. SUMMARY AND RECOMMENDATIONS 127

REFERENCES 134

APPENDIX A 143

APPENDIX B 145

APPENDIX C 147

APPENDIX D 149

LIST OF FIGURES

Figure Page

1. The Human Eye 33
2. Relationship of Eye Pointing Coordinates to CR Displacement 34
3. Infrared Image of the Pupil and the Corneal Reflection . . 35
4. Honeywell MK1 Oculometer 38
5. Video Output Waveform 39
6. Computer-Camera Interface Unit 42
7. Relationship of Computing Functions to Camera Output Signals 46
8. Derivation of Dilation and X- and Y- Displacement 50
9. Effect of "Type A" Error on Measurement of Vertical Displacement 59
10. Effect of "Type B" Error on Measurement of Vertical Displacement 61
11. Effect of "Type A" Error on Measurement of Horizontal Displacement 64
12. Effect of "Type B" Error on Measurement of Horizontal Displacement 66
13. Calibration Stimuli 73
14. Stimulus Situation 2 80
15. Stimulus Situation 3 81
16. Stimulus Situation 4 82
17. Uncorrected Eye Pointing Positions for Subject 1 Viewing Stimulus Situation 1 92

Figure Page

18. Uncorrected Eye Pointing Positions for Subject 2 Viewing Stimulus Situation 1 93

19. Uncorrected Eye Pointing Positions for Subject 3 Viewing Stimulus Situation 3 94

20. Corrected Eye Pointing Positions for Subject 1 Viewing Stimulus Situation 1 101

21. Corrected Eye Pointing Positions for Subject 2 Viewing Stimulus Situation 1 102

22. Corrected Eye Pointing Positions for Subject 3 Viewing Stimulus Situation 1 103

23. Corrected Eye Movements for Subject 1 Reading Stimulus Situation 2 105

24. Corrected Eye Movements for Subject 1 Waiting for Stimulus Situation 3 106

25. Corrected Eye Movements for Subject 1 Reading Stimulus Situation 3 107

26. Corrected Eye Movements for Subject 1 Waiting for Stimulus Situation 4 108

27. Corrected Eye Movements for Subject 1 Reading Stimulus Situation 4 109

28. Corrected Eye Movements for Subject 2 Reading Stimulus Situation 2 110

29. Corrected Eye Movements for Subject 2 Waiting for Stimulus Situation 3 111

Figure Page

30. Corrected Eye Movements for Subject 2 Reading Stimulus Situation 3 112

31. Corrected Eye Movements for Subject 2 Waiting for Stimulus Situation 4 113

32. Corrected Eye Movements for Subject 2 Reading Stimulus Situation 4 114

33. Corrected Eye Movements for Subject 3 Reading Stimulus Situation 2 115

34. Corrected Eye Movements for Subject 3 Waiting for Stimulus Situation 3 116

35. Corrected Eye Movements for Subject 3 Reading Stimulus Situation 3 117

36. Corrected Eye Movements for Subject 3 Waiting for Stimulus Situation 4 118

37. Corrected Eye Movements for Subject 3 Reading Stimulus Situation 4 119

38. Uncorrected Eye Movements for Subject 2 Reading Stimulus Situation 2 120

39. Uncorrected Eye Movements for Subject 2 Waiting for Stimulus Situation 3 121

40. Uncorrected Eye Movements for Subject 2 Reading Stimulus Situation 3 122

41. Uncorrected Eye Movements for Subject 2 Waiting for Stimulus Situation 4 123

Figure Page

42. Uncorrected Eye Movements for Subject 2 Reading Stimulus Situation 4 124

43. Pupil Dilations for Subject 1 Reading Stimulus Situation 2 125

LIST OF TABLES

Table		Page
I.	Oculometer Output for Various Target Locations	70
II.	X- and Y- Calibration Data	75
III.	X- and Y- Linearity Errors	76
IV.	X- and Y- Calibration Data Subjects 1 - 3	85
V.	Error Table for Subject 1	89
VI.	Error Table for Subject 2	90
VII.	Error Table for Subject 3	91
VIII.	X- and Y- Linearity Correction Factors	98
IX.	Error Table for Subject 3 Based on Corrected Horizontal Calibration Axis	99

CHAPTER 1

INTRODUCTION

The process of learning relies primarily upon sensory information reaching the learner via either or both the auditory and visual channels. While some occasions arise when sensory inputs from the tactile channel are also important to learning, it is much less often that the learner relies upon the remaining senses.

Considering the relative importance of the auditory and visual sensory input channels, it is difficult to determine which of these is more important in learning. A great deal would most certainly depend on the nature of the learning task. Feinstein (1970) identified the visual channel as ". . . our primary sensory input channel".

Considering types of learning that depend on appropriate stimulation of the visual channel, if appropriate stimulation of the visual channel is dependent upon visual response, then one of the factors that affects learning is visual response. It is important therefore that studies of learning involving the visual sensory channel take into account the visual response of the learner.

Educators have recognized the importance of the visual response (eye movements) in learning for nearly a century. The earliest eye movement studies were conducted in relation to reading (Javal, 1879) and consisted of directly observing and recording the movements of a subject's eyes while reading. One of the most significant discoveries that resulted from this early research was that in reading a line of text, the eye moves in a series of rapid jerks, (called saccades) interspersed with relatively long pauses (called fixations). This

discovery replaced the previously held traditional belief that when a person reads, his eyes move smoothly and uninterruptedly along the line of print. Tinker (1965) reported that research activity in this area became more vigorous after 1900. He indicated that several hundred investigations of eye movements in relation to reading have been reported and ". . . have contributed much to an understanding of how children learn to read."

The growth of technology during the twentieth century brought about many developments and improvements in methods of measuring and recording eye movements (oculography). By 1971, there were reports (Feinstein, 1970) of as many as seven different methods of oculography and each method included a number of variations in technique. During this same time period, interest in oculography began to spread to a variety of other disciplines, including ophthalmology, biomedical engineering, and psychology. Within education, eye movement research spread to a number of other related fields, including studies of learning in relation to novelty of a stimulus (Berlyne, 1958), familiarity and complexity of a stimulus (Neisser, 1964), size of a visual display (Enoch, 1959), attention (Guilford and Hackman, 1936), problem solving (Teichener and Price, 1966), emotionalism (Luborsky, Blinder and Mackworth, 1963) and perception and information processing (Hebb, 1949; Gould and Schaffer, 1965).

Another result of the growth of technology has been an increase in the importance of the visual sensory input channel in the field of education. The development of offset printing and the subsequent mass distribution and utilization of books by educational institutions; the development of programmed instruction; the introduction of films, trans-

parencies and educational television into the classroom; the introduction of special education for deaf children and mentally retarded; and most recently, the introduction of computer based instruction all rely heavily on sensory input to the learner via the visual channel.

Instructors responsible for constructing educational materials have relied to a large extent on the generalized findings that have come out of eye movement studies to guide them in designing visual instructional materials. However, frequently there is little similarity between the experimental setting and the educational setting to which generalizations must be drawn. Because most oculography equipment currently available does not readily lend itself to use outside the laboratory, instructors have had no way of evaluating the adequacy of their instructional materials to elicit appropriate visual responses. For example, in an experiment conducted by Wolf, et al. (1970) students were presented with a television scene of an instructor demonstrating the operation of a model airplane. Low IQ students tended to look at the instructor's tie rather than at the model airplane the instructor was demonstrating. This visual response would suggest that the instructor had failed to accomplish the stimulation of the visual channel that he had set out to bring about when he designed the scene. Improvement in visual response and perhaps in learning may be brought about by re-designing existing educational material.

The first purpose of this study is to report and document the development of the infrared computer based oculometer designed for monitoring and recording eye pointing coordinate data and pupil dilations of subjects involved in various learning tasks. The unique features of the computer based infrared oculometer are that it will operate under most normal

lighting conditions, and that it will require only a minimum of physical restraint of the subject (chin rest). In addition, it will output data onto 9-track magnetic computer tape that will permit calculation of eye position, eye pointing direction and pupil dilation once every 33.3 milliseconds. This will permit data to be easily analyzed.

The data recorded by the infrared computer-based oculometer system will simply consist of a measure of pupil dilation and a measure of the displacement of the center of the corneal reflection from the pupil center, recorded once every thirtieth of a second. In order to derive the more traditional measures of eye movement such as number of fixations per line of text, mean length of fixation, number of blinks per unit time, etc., further processing of the oculometer output will be necessary. However, because the oculometer output will be available on 9-track computer tape, it will be relatively simple to prepare computer programs that will quickly read the oculometer output tape and output summaries of these more traditional eye movement measures.

A second purpose of this study is to document the reliability, validity, and accuracy of the infrared computer based oculometer. This will be referred to as establishing the proof of performance of the system. This problem is essentially a measurement problem and is necessary when any new measuring instrument is developed.

One way of establishing the proof of performance (reliability, validity and accuracy) of a measuring instrument is to compare the output of the system under test with the output of other systems whose proof of performance is already well established. This approach

was not used with the infrared computer based oculometer for several reasons. First, it is difficult to obtain a system with established proof of performance to permit the necessary data to be collected. Second, it is difficult, although possible, to configurate hardware so that two systems, the standard and the system under test, could simultaneously monitor a subject's eye movements. Most important however, it is expected from the design parameters of the infrared computer based oculometer, that its reliability and accuracy will exceed the reliability and accuracy of most known available systems. This would mean that determination of accuracy and reliability by comparison would have questionable merit.

An alternative method of establishing proof of performance of the computer based oculometer system, and the one that will be followed in this study consists of documenting the performance of the infrared computer based oculometer system in relation to a series of simple, definable sub-tasks which are known to constitute the overall task that the system is expected to perform. These findings can then be generalized to describe the performance of the complete oculometer system. For example, since the capability of the oculometer to determine where a subject is looking is based on its capability to measure linear displacement (both horizontal and vertical) between two defined points within the image of the eye, one sub-task of the system is to measure small linear distances. Inadequate performance of the infrared computer based oculometer system while measuring small linear horizontal and vertical distances would certainly be one limitation of its capability to determine where a subject is looking. Chapter

three of this study includes the identification of other sub-tasks, and documentation of the performance of the infrared computer based oculometer in relation to these sub-tasks, and in turn, in relation to the main task of determining where a subject is looking.

This study will also demonstrate the use of the infrared computer based oculometer for analyzing eye movements during learning by recording and analyzing the eye movements of a small number of subjects involved in three different types of learning tasks. The learning tasks will be selected from available instructional material in the Division of Educational Research Services and will be displayed on the cathode ray screen of an IBM 1500 CAI terminal. The displays will include one display consisting of text only, one display consisting of some text combined with an illustration and one display consisting of a multiple choice question which requires the subject to select a response visually.

Summary

This chapter discussed the importance of the visual sensory input channel to learning and education and discussed the importance of knowing where the learner is looking during various learning tasks. Visual response of learners can be used as a basis for improving visual instructional materials. This chapter also identified the problems to be investigated in this study.

Chapter two of this study will describe the various methods that have been developed for monitoring and recording eye movements and will discuss some of their advantages and shortcomings. This chapter will also present a summary of the findings resulting from eye movement

research. The third chapter will describe the infrared computer based oculometer in detail and will present proof of performance data for the system. Chapter four will outline the methodology followed to collect and analyze eye movement data using the infrared computer based oculometer and will present the findings. Chapter five will present a summary of this study together with conclusions and some recommendations for further research.

CHAPTER II

REVIEW OF LITERATURE

Introduction

Since the visual system is one of man's primary input channels, it is important to understand how this system functions. Eye movement research or oculography began during the latter half of the nineteenth century and since then has been taken up by researchers in a variety of different fields with different goals in mind.

Biomedical engineers have studied eye movements in order to better understand the nature of the total oculomotor system and the relationships that exist between the many complex elements that constitute this system. To this end, they have developed computer based simulation models of the oculomotor system. Research by biomedical engineers can ultimately lead to a better understanding of how information is processed in the brain.

Opthalmologists have studied eye movements primarily from a medical standpoint. The development of improved oculographic techniques can benefit the opthalmologists greatly in the diagnosis and perhaps in the correction of certain eye defects.

Eye movement research has been a subject of interest to both educators and psychologists since Huey published his book on the psychology and teaching of reading in 1908 (Tinker, 1965). Since a large proportion of education is presented through the visual channel, eye movement research can provide information to educators about improving the effectiveness of instruction, whether it be by changing

the stimulus situation that is presented to the learner, or by modifying the looking behavior of the learner.

This chapter will review the methods that have been developed for measuring eye movements and will summarize the findings of eye movement studies in terms of the kinds of eye movements that have been reported.

Methods of Oculography

Yarbus (1968) and Feinstein (1970) discuss the various methods of oculography that have been developed, each of which will be identified and described briefly here.

Subjective Method

Historically, this method of oculography was the first to be used. It involves an observer who simply looks at the eyes of a subject and manually records his observations of the subject's eye movements. This method has been particularly useful in studying eye movements of infants (Greenberg and Weizmann, 1971) since no external equipment such as head restraints and bite bars is needed. Feinstein (1970) points out that "To this day, direct observation of a patient, while he attempts to follow an object . . . is used as a clinical test to reveal any nystagmus or gross disorders associated with the eye movement system."

Several modifications of this method of oculography have been reported wherein the subject, rather than an observer is responsible for determining and recording his eye movements. One such modification involves the use of "after-images". Several experimenters including Dodge (1907), Helmholtz (1925), Barlow (1952), and others used this

method which generally involves having the subject look at a bright wedge of light until the retina is fatigued. After the wedge of light is extinguished, a clear after-image, fixed relative to the retina is visible to the subject. The subject is required to report the position of the after-image he sees while looking at a stimulus target placed within his visual field. Since the after-image is fixed relative to the retina, any displacement of the perceived position of the after-image relative to the target is the direct result of a change in the point of fixation by the subject.

Kaufman and Richards (Richards and Kaufman, 1969, Kaufman and Richards, 1969) used the "Haidinger Brush" technique to enable a subject to determine and record his own eye fixations. This technique uses a slide projector equipped with a blue-light filter and a motorized polaroid filter. The subject is instructed to look at a screen on which slides containing the desired stimuli are projected, using this specially equipped slide projector. Whenever the researcher wishes to have the subject report his point of fixation, he simply turns on the motor which briefly spins the polariod filter. Because the fovea is equipped with thousands of blue-light absorbing radially oriented crystals whose absorption pattern lies along radii from the center of the fovea, linearly polarized light will be absorbed more strongly in some parts of the fovea than others. As a result, the subject sees a "brush" or wedge of light on the screen, perpendicular to the direction of polarization. Because the image thus produced is stable with respect to the fovea, it quickly disappears (stabilized image). However, when the polarizing filter is spinning, the brush is moving relative to the fovea, making it visible to the

subject, who reports seeing a "spinning propeller" on the screen. The point on the screen where the subject reports seeing the spinning propeller is the point which the subject was fixating when the polaroid filter was rotated.

Feinstein (1970) describes after-image as offering ". . . one of the largest dynamic ranges of all methods of oculography." However, he goes on to point out the shortcomings of all subjective methods of oculography stating that ". . . subjective measurements, though very useful, give no quantitative record of movement nor can they give any temporal information beyond a crude estimation".

Mechanical Method

The mechanical method of oculography represents researchers' earliest attempts to quantify measurements of eye movements. Feinstein (1970) discussed briefly the work of Delabarre and Huey whose efforts at mechanically coupling a recording apparatus to the eyeball he described as ". . . a remarkable achievement."

One extension of the mechanical method of oculography involved the use of a contact lens, attached to the eye, and linked either optically or magnetically to some recording apparatus. Cornsweet (1956) and others used a contact lens with a tiny mirror mounted on it. The image of a light source, placed before the eye of a subject wearing the lens, was reflected by the mirror to a continuously moving photographic film. This gave a permanent quantitative record of eye movements. Yarbus (1968) developed a number of "caps" designed to be attached to the eyeball by using suction, thus avoiding slippage. The caps which resembled a contact lens reflected a beam of light which traced a record on

photosensitive paper. Using "caps" Yarbus conducted many investigations into the nature of eye movements. His findings are probably among the most comprehensive and precise available to this day. Robinson (1964) used a set of coils imbedded in a contact lens to measure eye movements. The coils were exposed to two magnetic fields in quadrature and produced output voltages proportional to both horizontal and vertical eye movements.

While mechanical methods involving contact lenses or caps are by far the most sensitive, it must be pointed out that any mechanical method which necessitates the attachment of foreign objects to the eye suffers from the disadvantage of introducing additional mass on the eyeball. The resulting discomfort for the subject, and altered dynamics of the oculomotor system limit the desirability of this method of oculography.

Direct Optical Methods

Barlow (1952) described a method of oculography that permitted a photographic record of eye movements to be made without the use of caps or contact lenses. He placed a tiny globule of mercury on the anesthesized cornea of the subject's eye and reflected a beam of light from the mercury to a continuously moving photographic film.

A variety of other direct optical methods which did not require the introduction of any foreign object or substance into the eye were developed. Dodge and Cline (1901) reflected a point source of light directly from the cornea and recorded it on a continuously moving photographic film. Tinker (1931) and Taylor (1959) describe applications of this principle of eye movement recording in devices designed to study

eye movements during reading. While many different variations of this method of oculography have been developed for studying eye movements, perhaps the one that has been most widely used to this time is that developed by Mackworth (1967). Mackworth developed a stand camera which utilized a beam splitter and which recorded a composite image consisting of the target being viewed with the corneal reflection superimposed on the target, indicating where, on the target the subject was looking. A variety of methods of recording this composite image were developed. These included a polariod camera for fast photographic processing, a 16 mm. movie camera for capturing temporal information or a television camera connected to a video tape recorder. The light source used to create the corneal reflection could be fitted with an infrared filter, provided that the recording device was also modified to record infrared light. This had the desirable effect of minimizing the distracting effect of the light source.

While the Mackworth eye movement camera is likely one of the most commonly used oculographic instruments, it offers two major disadvantages. First, the analysis of eye movement data recorded in this manner is an extremely slow and tedious process. Second, and perhaps most important, in order to insure accuracy, the subject's eye must remain fixed relative to the camera. This is generally accomplished by fitting the subject with a bite bar which he must clench firmly in his teeth throughout the recording session.

Electro-oculography

A standing potential is known to exist between the cornea and the retina of the eye. By attaching electrodes to the left and right of the

eye and above and below the eye, the corneo-retinal potential may be recorded. Eye movements are recorded as changes in corneo-retinal potential and are free from interference due to head movement. Yarbus (1968) stated that ". . . electro-oculography is used with fair success by many workers when highly accurate records of eye movements are not required". Feinstein (1970) points out that the main difficulties associated with electro-oculography are electrode polarization, electrical interference or "noise", and data interpretation.

Electronic Measurement Methods

Unlike the direct photographic methods of oculography, which rely on the direction of reflected light to determine where the eye is looking, electronic measurement methods rely on a change in the quantity of light picked up by a photocell. While there are a number of variations, the technique relies on the principle that less light is reflected from the sclera than from the pupil. When a patch of light is directed onto the limbus, (the scleral-pupil boundary), and the quantity of reflected light is projected onto a photocell, the photocell output will vary as the eye moves and varies the position of the limbus relative to the light source. Cornsweet (1956) used this principle in a system which scanned light rapidly across the eye and used a photomultiplier to monitor the level of reflected light. The length of time taken from the start of the scan to a rise in the photomultiplier output was proportional to the horizontal eye position. Rashbass (1968) developed a tracking system consisting of a cathode ray tube and a photomultiplier tube. A spot on the cathode ray tube was projected to the limbus. When the eye moved, the spot moved to the cornea and was reflected to a photomultiplier

tube. The photomultiplier tube output was used to reposition the spot to the limbus. The movement of the spot was therefore proportional to the movement of the eye. As was the case with the direct photographic methods of oculography discussed earlier, the subject's head had to be immobilized, since movements of the head would result in displacement of the limbus, thereby giving false readings.

Young (1962) mounted photocells and lamps in a pair of goggles to be worn by the subject, thereby eliminating artifacts that result from unrestrained head movement. Feinstein (1970) also used goggles similar to Young, however, he utilized infrared light sources, thereby eliminating the distraction of visible light. The major advantage of electronic methods of oculography is the ability to measure eye movements without contact with the eye. While the use of goggles limits the amount of head restraint that must be imposed on the subject, some head restraint is nonetheless needed if one is to determine precisely where, within a target a subject is looking. Freedom of head movement would make it possible for the subject to change his point of fixation by moving his head rather than his eyes. Such a change would go undetected unless an additional monitor was added to simultaneously record subject's head position.

The Infrared Computer Based Oculometer

In 1969, Mason and Merchant described a method of oculography which provided relatively unrestrained head movement. The system consisted of an image dissector tube which was made collinear with an infrared light source and which was positioned adjacent to the target

area. The infrared light was absorbed by the skin surrounding the eye and by the sclera. Infrared light entered the pupil and was focused on the retina, which tended to scatter the light, backlighting the pupil to some intermediate level of intensity. In addition, the image of the infrared light source was formed as a bright corneal reflection. This image of the eye was focused on the photocathode of an image dissector. An analog computer was connected to the image dissector. The image of the eye was scanned and analyzed by the computer and the output included horizontal and vertical eye position, horizontal and vertical coordinates of eye pointing direction, and pupil dilation. In 1970, Hillsman, Willams and Roe interfaced the image dissector with a digital computer.

The purpose of this report is to document the development of a computer based infrared oculometer which is similar in principle to those reported above but which used a Raytheon television camera equipped to sense infrared and which was fully interfaced to a small digital computer programmed to determine and record horizontal and vertical eye position, horizontal and vertical coordinates of eye pointing direction and pupil dilation once every thirtieth of a second. Applications of the computer based infrared oculometer to educational problems will also be presented.

Types of Eye Movements

Classical eye movement theory identifies three major types or classes of eye movements; conjugate or versional movements, vergence and tremors.

Conjugate or Versional Movements

Conjugate eye movements are movements during which both eyes move in the same direction. There are three kinds of conjugate eye movements.

Small conjugate movements are involuntary and occur during fixation of a stationary target. Feinstein (1970) described small conjugate movement as ". . . a slow drift which tends to displace the image of the target from the fovea, followed by a small, very rapid flick . . . opposite in direction to that of the drift . . . tending to relocalize the target image on the fovea." Mason and Merchant (1969) refer to small conjugate eye movements as "eye noise" or "hunting" and describe them as consisting of displacements as large as two-tenths of a degree away from the point of fixation and recurring at a rate of about five times per second. This angular displacement, expressed as a linear displacement on a target area twenty inches from the eye of the subject would represent a linear displacement of about .07 inches at the target. This means that while a subject is fixating on a point twenty inches away, the eye will actually be looking somewhere within a circle around this point, approximately .14 inches in diameter. Yarbus (1968) conducted a series of experiments using his "caps" and found that the size of small conjugate eye movements is a function of the length of fixation and that it can vary ". . . between 1 and 25 minutes of angle. The minimal dimensions . . . between 2 - 5 minutes of angle. The maximal dimensions . . . approximately 40 to 50 minutes of angle". Yarbus also reported that the duration of small conjugate eye movements depends on their amplitude and is approximately 100 to 200 milliseconds with some lasting as long as several seconds. Referencing these findings to a target area twenty inches from the eye of a subject suggests that small conjugate eye movements could lie in a circle around the point of fixation slightly larger than one-half inch in diameter. West and Boyce (1968)

reported that the rate of drift during a small conjugate eye movement was about 5 minutes of angle per second. They found, as did Yarbus that the duration of drift varied from approximately 100 milliseconds to several seconds.

The second type of conjugate eye movement is the saccade, a very rapid movement of the eye whose primary purpose is to move the eye from one point of fixation to another. Saccades can be either voluntary or involuntary. Yarbus (1968) reported that the amplitude of a saccade rarely exceeded 15 to 20 degrees of arc. Research indicates (Feinstein, 1970) that saccades rarely occur more than once every 200 milliseconds, and that the peak velocity of the eye during a saccade can be as high as seven hundred degrees of angle per second. Spache (1962) reported that the shortest duration of an effective saccade was 166 milliseconds and that the minimum time for a saccade to occur was 33 milliseconds. Yarbus (1968) found that the total time taken for a saccade to occur was 10 to 70 milliseconds, depending on its size.

The final type of conjugate eye movement is referred to as smooth pursuit. Smooth pursuit eye movements occur when the eye tracks a smoothly moving target that is moving at a velocity of 35 degrees of angle per second or less (Feinstein 1970). Yarbus (1968) conducted experiments wherein subjects were required to imagine that they were tracking a smoothly moving object. He found that ". . . it always appeared to the subject that the movements of his eyes were smooth and continuous, in fact they consisted entirely of separate fixations, saccades, convergences and divergences." In experiments where the subject was required to view a moving object, Yarbus found that the subject could

start or stop visual pursuit of the object at will but could not ". . . interfere voluntarily with the actual process of pursuit and change its speed deliberately." In his analysis of velocities of pursuit, Yarbus found that with angular pursuit velocities of more than five minutes of angle per second, smooth pursuit was possible and was characterized by the presence of small conjugate eye movements. Satisfactory tracking did not seem possible at speeds exceeding 200 degrees of angle per second.

Vergence

Vergence eye movements are movements during which the eyes move in opposite directions. Normally the visual axes of the two eyes intersect at some distance from the subject. Divergence refers to vergence movements that increase this distance while convergence refers to vergence movements that decrease this distance. Feinstein (1970) pointed out that ". . . the amplitude range for vergence movements is much smaller than that for versional [conjugate] movements."

Tremor

Tremor refers to very small, non-conjugate movements of the eyes observed under conditions of fixation (Adler and Fliegleman, 1934). Records of tremor have shown it to consist of angular displacements of a few seconds of angle at frequencies of 30 to 80 displacements per second. Feinstein (1970) states that ". . . it is undecided whether they [tremor eye movements] have any physiological significance or whether they simply represent noise."

Of the three classes of eye movements discussed, it would appear that the ones most relevant to studies of learning and attention

are conjugate eye movements. The fact that both eyes move together during conjugate eye movements means that records obtained from one eye are sufficient to describe the subject's looking behavior. This study will document the feasibility of using the infrared computer based oculometer for recording eye movements as they would be used in studies of learning and attention in the field of education.

Eye Movement Research

Dodge (1903) was among the first to begin to analyze eye movements. His distinction between saccadic and smooth pursuit eye movements was investigated further by Westheimer (1954) and Rashbass (1960). Rashbass showed that tasks involving various combinations of displacement and velocity evoke smooth movement responses determined by the task displacement. He concluded that these two different kinds of eye movements were the result of two independent neurological systems.

Volkman (1962) compared vision during saccades with vision during fixations by means of three psychophysical tasks, in an attempt to determine a basis for the lack of apparent blurring during voluntary saccades. He concluded that while vision was not blanked out during voluntary saccades, it was significantly depressed. Matin, Matin and Pearce (1969) sought to further clarify the mechanisms underlying the normal stability of visual direction for stationary objects during voluntary saccades. They used specific points during the occurrence of a saccade as trigger points for the presentation of stationary test flashes to subjects. Subjects reported the perceived direction of motion of a test flash, relative to a fixation target which was

extinguished prior to the presentation of the test flash. Classical theory (Helmholtz, 1866; Whitteridge, 1964) suggests that an "extra-retinal" signal occurring outside the retina, and proportional to eye position, acts to compensate for the shift of the retinal image resulting from the movement of the eye, thus a stationary object does not appear to change location during a saccade. Matin, et al. concluded from their findings that there appeared to be an extraretinal signal, but that the extraretinal signal produced was not proportional to eye position. It appeared to be proportional to the elapsed time since the beginning of the saccade. Pearce and Porter (1970) investigated the possibility that a subject's criterion for visual sensitivity was being depressed during voluntary saccades. They developed a criterion-free measure of visual sensitivity and using it to measure saccadic supression, demonstrated that there was a decrease in visual sensitivity as much as 150 to 200 milliseconds prior to the occurrence of a voluntary saccade.

Krauskopf, Cornsweet and Riggs (1960) analyzed horizontal components of eye movements during both monocular and binocular fixation. They found that saccades in one eye seemed to always be accompanied by saccades in the other eye, almost always in the same direction, and about the same size. Drift and tremor of the two eyes are not correlated. Huang and Smith (1970) recorded vertical binocular eye movements and concluded that movements of the two eyes were not exactly conjugate during saccades. They found a time variation of less than 100 milliseconds. Smith, Schremser and Putz (1971) confirmed these findings and concluded that this indicated a possible feedback system between the oculomotor control systems of the two eyes.

Young and Stark (1963) developed and tested a sampled data model to describe the action of the control system of the eye. Robinson (1964, 1965) conducted studies of both the saccadic and the smooth pursuit eye movement systems. He concluded that while the sampled data model of Young and Stark was satisfactory for saccadic movements, it seemed to be inadequate for smooth pursuit movements.

A number of eye movement studies comparing the performance of subjects of various ages have been reported. The aim of such studies is to investigate the developmental aspect of eye movements. Zinchenko, van Chzhi-Tsin and Tarakanov (1963) showed that three year olds tended to fixate longer, made little attempt to search for distinctive features in a display, and stayed within the area of a figure, compared to six year olds. They concluded that eye movements in a growing child develop towards locating distinctive features in visual stimuli.

Vurpillot (1968) studied eye movements of children required to judge stimuli as the same or different. She found that children under six years old tended to make errors in judgement due to insufficient scanning while nine year old children made virtually no errors in judgement.

O'Brien and Boersma (1970) studied the eye movements of 92 female conservers and non-conservers. They found that conservers showed greater perceptual activity in the form of scanning behavior than non-conservers.

Mackworth and Morandi (1967) and Mackworth and Bruner (1970) compared eye movements of adults and children on scanning tasks. Adults showed a greater facility for fixating areas judged to be more inform-

ative. They also tended to have longer "leaping" eye movements and shorter fixations.

Miller (1969) recorded eye movement latencies of eight year old children and college students. Subjects were required to change their point of fixation from a central fixation light to one of four randomly illuminated target lights displaced equally in each of four directions from the central fixation light. He found that eight year old children had a longer latency. In addition, he observed that differences in latencies among eight year old children were dependent on the closeness of the target to the central fixation light. No such differences were observed among college students.

Eye movements have been used as the dependent variable in a number of studies of cognitive behavior. Luborsky, Blinder and Mackworth (1963) studied eye movements of subjects during a "search" task. They found that subjects having more fixations were better able to recall the content of perceptual images. Teichener and Price (1966) studied eye movements of subjects given the task of studying a letter sequence in order to determine the next letter in the sequence. They found that a reduction in scanning and an increase in attention to detail resulted in correct solution of the task.

Gould et al. (Gould and Schaffer, 1965; Gould and Brown, 1967; Gould, 1967; Gould and Schaffer, 1967; Gould and Dill, 1969; Gould and Peeples, 1970) conducted a series of experiments to study eye movements of subjects during pattern recognition tasks. They found that subjects spent less time looking at incorrect responses than they did looking at correct or matching responses. They also reported a quadratic

relationship between the amount of information contained in a stimulus and the duration of fixation. They concluded that the duration of fixation depended on the amount of cognitive activity required for a specific task.

Faw and Nunally (1967, 1968) reported studies of eye movements of children viewing pairs of pictures differing on a number of different dimensions. They found that subjects spent more time fixating complex and novel stimuli. Children spent more time fixating stimuli having negative affective value while college students spent more time fixating stimuli having positive affective value. Subjects also spent more time fixating stimuli constructed by incongruous juxtaposition, attempting to resolve informational conflict.

Conklin, Muir and Boersma (1968) studied eye movements of "field independent" and "field dependent" subjects given the task of searching for missing parts within a picture. They found that field independent subjects fixated with greater frequency in high-information areas of the stimulus field. They concluded that field independent subjects employed more effective visual search strategies. Boersma, Muir, Wilton and Barham (1969a, 1969b) studied eye movements of field independent and field dependent subjects on "imbedded figures" tasks and "anagram" tasks. On the imbedded figures task, field independent subjects exhibited more shifts between the target figure and the alternatives while on the anagram task, they required less time to scan the 5 letters of the anagram.

Drake (1970) compared eye movements of "impulsive" and "reflective" subjects on the Matching Familiar Figures test. Reflectives tended to

look at a larger area of the figure before responding than did impulsives.

Muir (1971) studied eye movements of normal and mentally retarded subjects during directed search tasks and discrimination learning. His results suggested a visual attention deficiency in mentally retarded subjects. Yewchuk (1972) studied eye movements of mentally retarded subjects during a discrimination shift learning task. Eye movement data provided no evidence that individual differences in learning discrimination tasks could be attributed to an attention deficit.

Hess and Polt (1960) and Hess (1965) studied pupil dilation of subjects presented with a variety of stimuli. They suggest that pupil dilation is a measure of interest, emotion, attitude, and on-going cognitive process. Clark and Johnson (1970) suggested that pupil dilation could be related to cognitive processing. Their results agreed with the findings of Kahneman and Beatty (1966) that the pupil dilates as short term memory is loaded and constricts toward normal size as material is recalled and short term memory is unloaded.

Noton and Stark (1971) suggested that eye movement studies of subjects looking at a variety of stimuli could provide information about whether cognitive processing of visual stimulus information was a serial or a parallel (Gestalt) process. They observed that in scanning a stimulus field, the subject followed a relatively fixed scanpath around a format of features. They discussed the significance of this "feature ring" in terms of recognition of stimuli. They concluded that " . . . the weight of the evidence seems to support the serial hypothesis" and that ". . . the internal representation or memory of an object is a

piecemeal affair".

A number of studies of eye movements in relation to learning tasks have been reported. McCormack et. al. (McCormack and Haltrecht, 1966; Haltrecht and McCormack, 1966; McCormack, Hannah, Bradley and Moore, 1967; Hannah and McCormack, 1968; Moore and McCormack, 1968; McCormack, Clemence, Tymm and Malabre, 1969; McCormack and Clemence, 1970) studied eye movement behavior of college students during a variety of paried associates learning tasks. These authors have provided a great deal of evidence in support of Underwood's (Underwood and Schulz, 1960) two stage learning model in which the first stage consists of learning the response and is followed by the second stage, which involves association of the appropriate pairs. They also found that slow learners tend to take longer during the first stage and they experience more difficulty in the second, that eye movements of "high-anxious" subjects differ from eye movements of "low anxious" subjects, and that time spent scanning the response of a paired associate item decreases as learning progresses.

Guba et al. (1964) studied eye movements of subjects during a television lesson. They defined a continuum of eye movements and found that "no observable movements" and "minimovements" were related to intelligence. They also performed density analyses for areas fixated by subjects and found age and intelligence differences.

Nunally, Stevens and Hall (1965) observed eye movements of children after they had learned to associate previously neutral stimuli with rewards. Five days after training, subjects spent significantly more time looking at stimuli previously associated with rewards. Webb,

Matheny and Larson (1963) used shock to condition eye movements of subjects. They found that subjects spent significantly less time looking at stimuli previously associated with shock. Schroeder (1970) used reinforcement to train eye movements of college students in a simultaneous discrimination task. He found that subjects fixated stimuli which had previously been reinforced.

Doran and Holland (1969) studied eye movements of subjects studying introductory psychology using programmed instruction. The study sought to determine differences in looking behavior of subjects studying programmed material with high and low "blackout ratios". The blackout ratio was used to provide an index of redundancy. When much material could be left out without affecting the error rate, it was said to have a high blackout ratio. They found that high blackout ratio material resulted in fewer fixations, shorter fixation time and shorter scan time, suggesting that high blackout ratio programs fail to evoke students' attention.

Perhaps no single field of study has shown as much interest in the study of eye movements as the field of reading. The first description of eye movements in reading was presented by Javal in 1879. He reported that the results of direct observation revealed that the eyes move along a line in quick jerks, with pauses between the jerks. Other attempts to measure and record eye movements of subjects while reading were made by Erdmann and Dodge (1898) using a telescope, by Miles (1928) using a "peephole", and by Shackwitz (1913) using a pneumatic capsule attached to the eyelid. A method pioneered by Dodge in 1901 and refined by Tinker in 1931 and Taylor in 1937 based

on the corneal reflection principle, led to more than a hundred studies involving eye movements during reading. Tinker (1965) presents a comprehensive review of eye movement studies in relation to reading.

A number of more practically oriented studies involving oculography have also been reported. Such studies have implications for technical and vocational education. Milton and his associates (Milton, Jones and Fitts, 1949, 1950; Milton, McIntosh and Cole, 1951, 1952, 1954; Milton and Wolfe, 1952), Barnes (1970), and Gainer (1964) conducted extensive research on eye movements of pilots under a variety of specified flight conditions. Their findings were used in the design of airplane and helicopter control panels and in the design of pilot training programs. Schroeder and Holland (1968) monitored eye movements of subjects presented with a vigilance task. Subjects were required to visually detect deflection of ammeters arranged in a simulated "control panel" configuration. They concluded that ". . . an eye movement can act as an operant, controlled by its consequences." They suggest that operant control of eye movements has important implications for human factor analysis concerned with attention.

One basic underlying assumption of educators involved in preparing visual instructional materials for students is that students will look at or attend to the appropriate visual material during the learning process. If the learner does not attend to the appropriate visual material during the learning process, then learning may be seriously inhibited. The study of eye movements can provide educators with feedback about the effectiveness of their visual material, whether it be a page or a picture in a text book, an overhead projectual, a test

item or a cathode ray screen of a computer assisted instructional system. Such feedback forms one essential part of the basis for producing improved visual materials for instruction. It can also form the basis for teaching students effective looking behavior.

It is apparent from the studies reviewed in this chapter that oculography has been a subject of interest to many researchers in many different disciplines over the past seventy years. The biggest single limitation to more extensive oculographic studies has continually been the limited sophistication of available hardware. Recent developments in electronics and computer technology have now provided some new possibilities for hardware that measures records and analyzes eye movements quickly, easily and unobtrusively. The purpose of this study is to document the development of an infrared computer based oculometer system designed and built with this end in mind. Chapter III describes the infrared computer based oculometer system and documents its performance while the remaining chapters illustrate some applications of this system to oculographic research in education.

CHAPTER III

DESCRIPTION OF THE INFRARED COMPUTER BASED OCULOMETER SYSTEM

Introduction

The importance of oculographic data to many fields, including education has been recognized for more than half a century. During this time, many attempts have been made to develop systems designed to acquire eye movement data. Chapter II briefly describes the basic methods of oculography that have been developed.

Each of the existing methods of oculography was developed to meet a specific need. For example, the Yarbus "cap" (Yarbus, 1968) was a very precise way to measure and record physiological characteristics of the eye, but it would be of little use to a researcher who wished to study eye movements of grade one children while reading. Similarly, the Mackworth camera is an excellent means of determining where a subject is looking, but the need for a bite bar places the subject in a highly artificial experimental situation.

The study of eye movements in relation to learning and attention requires that:

1. The measuring and recording apparatus be relatively unobtrusive.
2. The equipment require no mechanical attachment to the subject.
3. The equipment place as few unnatural constraints (such as restriction of head movement) on the subject as possible.
4. As many oculographic characteristics as possible be

recorded simultaneously.

5. The data be in a form that is readily accessible for analysis by computer.
6. The equipment be sensitive enough to detect, and fast enough to record all types of conjugate eye movements.

Since none of the systems currently being used for oculographic research meets all of these criteria, it is perhaps not surprising that "The number of studies of learning which have employed EM [eye movement] data is disappointingly small" (Fleming, 1969). The infrared computer based oculometer system described here is an oculographic system that will unobtrusively (using infrared light) and with a minimum of head restraint (chin rest) record eye-pointing direction and pupil dilation, once every thirtieth of a second.

The infrared computer based oculometer system is based on the corneal reflection method of oculography. The eye is illuminated with infrared light and the image of the eye is projected to the face of an infrared television camera which is connected via a special interface unit to a small digital computer. The computer rapidly analyzes the signal coming from the camera and calculates and records the displacement of the corneal reflection from the pupil center and the pupil dilation. One such set of data is recorded every thirtieth of a second. This chapter will describe in detail how the infrared computer based oculometer system operates.

The Eye

The human eyeball is approximately sperical and contains optical apparatus which includes two refracting elements, the cornea which is

the transparent, curved front portion of the eyeball wall, and the lens which is the refracting element with variable power. The iris, situated between the cornea and the lens acts to control the size of the opening at the front of the eye. (See Figure 1).

The sensory apparatus of the eye is the retina, a thin membrane of photoreceptors. The area of the retina possessing the highest degree of visual acuity is the fovea. (Feinstein, 1970).

The optical axis of the eye lies along a line joining the center of the pupil, the center of corneal curvature, and the fovea. The extension of the optical axis foreward from the eye indicates the point in space being fixated foveally by the eye. (See Figure 2).

The Infrared Image

In order to determine the position of the optical axis of the eye, and thereby determine its point of fixation, it is necessary to make the pupil center and the center of corneal curvature visible. This may be accomplished by illuminating the pupil with infrared light, which is not visible to the human eye. An observer, equipped with an infrared light detector, and situated on an axis collinear with the beam of infrared light being used to illuminate the eye would see the pupil as a bright luminous disc of infrared light against a dark background consisting of the sclera. Within the area of the pupil the observer would see a very small spot of light several times more intense than the pupil -- the corneal reflection. (See Figure 3).

Neither the center of the pupil nor the center of corneal curvature is directly visible as a result of infrared illumination of the eye, however both may be easily determined. Since the pupil appears

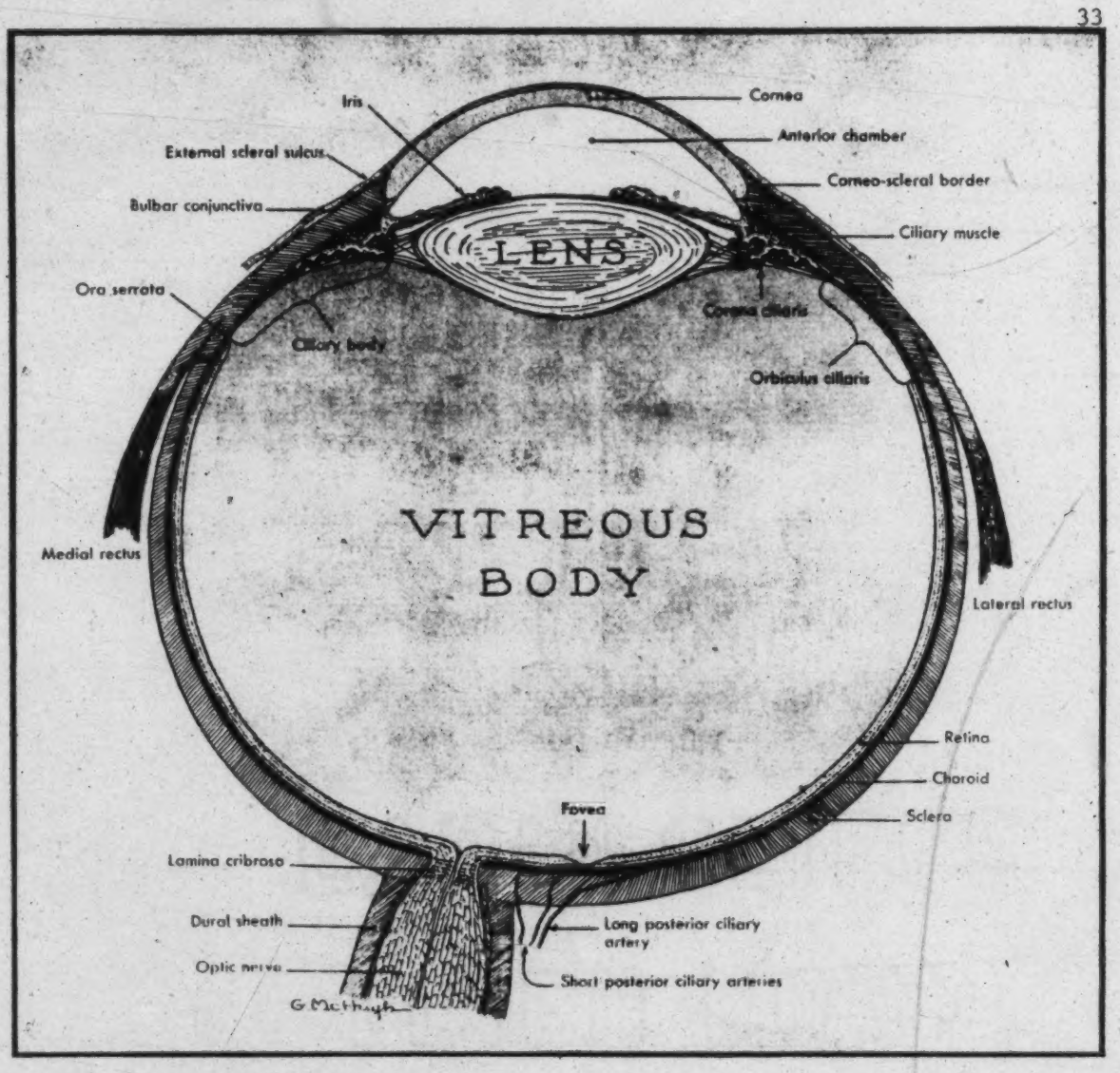


Figure 1

The Human Eye

(From P. C. Kronfeld, 1943)

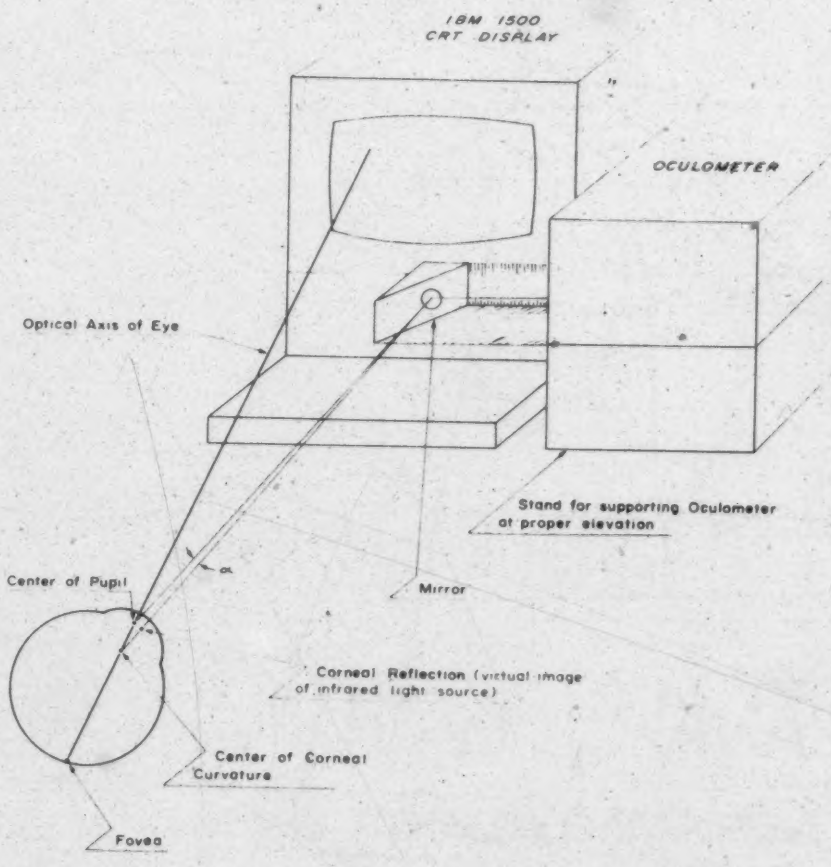


Figure 2

RELATIONSHIP OF EYE
POINTING COORDINATES
TO CR DISPLACEMENT

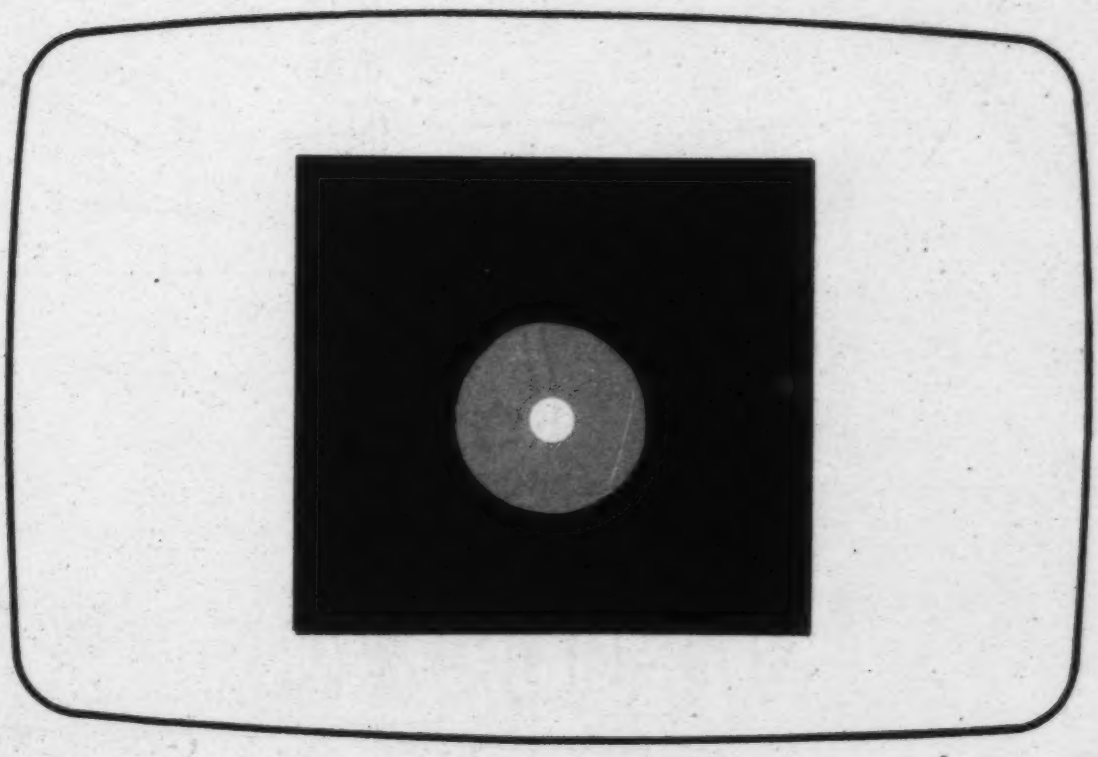


Figure 3

Infrared Image of the Pupil and the Corneal Reflection

as a circular disc, the center of the pupil can be located by bisecting the perpendicular to a tangent to the pupil. The cornea, because of its curvature will form a virtual image of the infrared light source as shown in Figure 2. This corneal reflection will lie on a line between the infrared source and the center of corneal curvature, therefore to an observer located at the source of infrared light, the corneal reflection would appear in exactly the same position as the center of corneal curvature (see Figure 2). The center of corneal curvature can therefore be found by bisecting the perpendicular to a tangent to the corneal reflection.

When the optical axis of the eye is pointed directly at the source of infrared light, an observer positioned at the source of infrared light would observe the corneal reflection to be at the center of the pupil. As the optical axis moves away from the source of infrared light, the corneal reflection will be displaced from the center of the pupil. The displacement of the corneal reflection from the center of the pupil is functionally related to the displacement of the point of fixation from the infrared source. Feinstein (1970) indicates that for angular displacements of less than 12 ½ degrees of angle, the relationship between eye pointing direction and relative corneal reflection displacement is linear. Mason and Merchant (1969) state that for movements of the subject's head, either sideways or up and down, ". . . there is only a small second order effect introduced" which may be ignored without appreciable error. It is therefore the displacement of the corneal reflection relative to the pupil center as viewed from the source of infrared light that will be used as the

basis for determining eye pointing direction.

The Camera

The complete infrared oculometer camera unit or optical head is shown diagramatically in Figure 4. This unit was designed and supplied by the Honeywell Radiation Center of Lexington, Mass. and consists of a source of infrared light, an infrared television camera and optical equipment that reflects the infrared light so that it is collinear with the pointing direction of the camera. A Sylvania quartz halogen lamp connected to a Superior type 10B variac or autotransformer serves as the variable intensity source of light. It is fitted with a lens and a Kodak type 87C gelatin filter which removes all visible light with the exception of a small amount of red giving it the appearance of a pilot light. A beam splitter directs the infrared light towards the eye of the subject. The image of the eye is projected through the beam splitter and a second infrared filter to the face of a Raytheon model 615 television camera specially equipped with an infrared sensitive RCA 4523A silicon vidicon tube.

The camera converts the infrared image of the eye into a standard 525-line interlaced video signal. The size of the video signal during any given scan line is determined by the nature of the image being scanned. When the black background of the sclera is being scanned, the level of the video produced is about 500 millivolts. When the image of the pupil is being scanned, the video signal rises to about 1.3 volts and when the corneal reflection is being scanned, the video signal exceeds 2 volts. Figure 5 shows the video signal produced by the camera when the various parts of the image are scanned.

HONEYWELL MK1 OCULOMETER

1 RAYTHEON MOD 615 CAMERA E/W RCA 4523A SILICON VIDICON

2 MIRROR

3 36" LENS E/W KODAK 87C FILTER

4 BEAM SPLITTING MIRROR

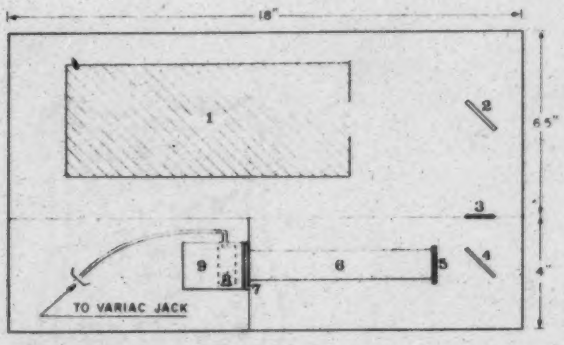
5 INFRARED GELATIN FILTER TYPE 87C

6 COLLIMATING TUBE

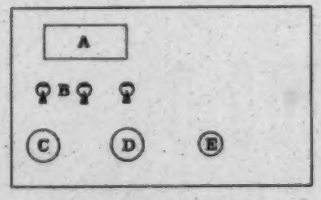
7 LENS

8 SYLVANIA TYPE FCR QUARTZ HALOGEN LAMP

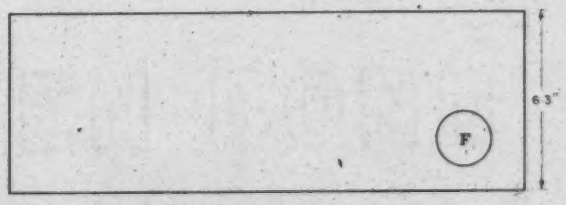
9 PARMOTOR MOD 8500 MUFFIN FAN



TOP VIEW
COVER OFF



SIDE VIEW



FRONT VIEW
COVER ON

A CAMERA ACCESS PORT

B TOGGLE SWITCHES

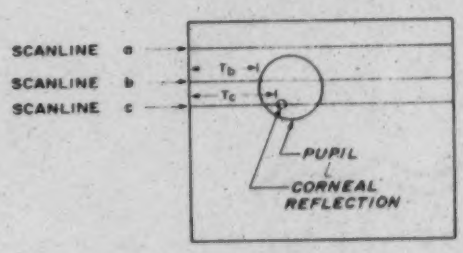
C SYNC OUTPUT JACK

D VARIAC JACK (TO SUPERIOR TYPE 10B VARIAC)

E VIDEO OUTPUT JACK

F PORT

Figure 4



VIDICON FACE

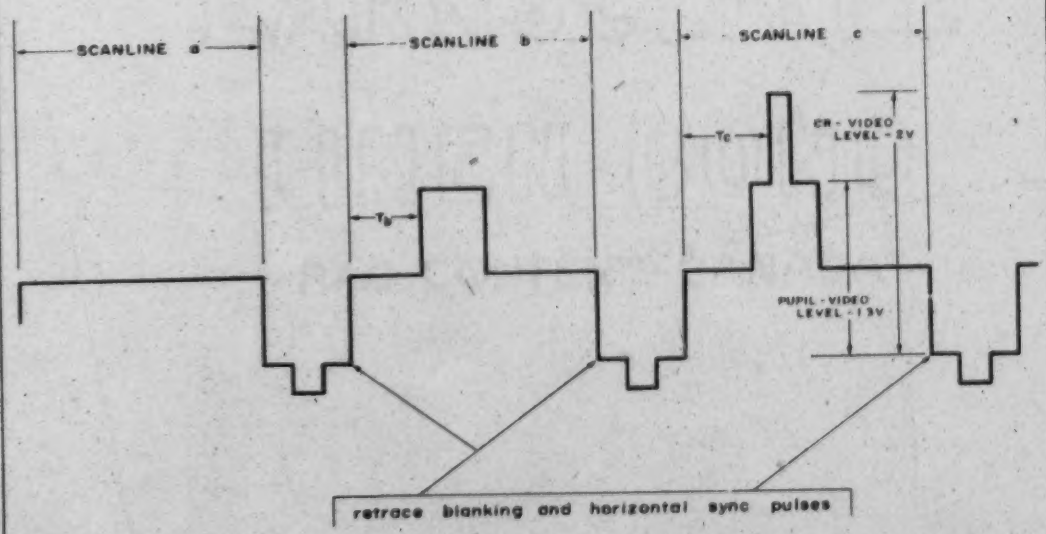


Figure 5

VIDEO OUTPUT WAVEFORM

In addition to the video signal described above, the camera also outputs horizontal and vertical synchronization pulses. A horizontal synchronization pulse is generated at the end of every scan line executed by the camera, therefore there are 15,750 horizontal synchronization pulses generated every second. A vertical synchronization pulse is generated whenever the scanning for one field has been completed and the camera is ready to start scanning a new field. This occurs sixty times per second.

The Computer-Camera Interface Unit

Perhaps the most important element of the entire infrared computer based oculometer system is the computer-camera interface unit. This unit serves two major functions. First, because it is necessary to use the computer to process the camera output, and because the size and shape of the camera output signals are not compatible with the input requirements of the computer, this unit must modify the size and shape of the camera output signals to conform to the input requirements of the computer. Second, the computer-camera interface unit identifies and monitors each scanline generated by the camera. Based on changes it detects in the camera output level relative to a time base it generates, it determines whether a pupil and/or a corneal reflection has been intercepted, the position of the point of intercept relative to its time base, and the instant when a given scanline has reached the end of its scan.

This information is available to the computer to be used as the basis for determining oculometer output.

A simplified block schematic of the computer-camera interface unit is shown in Figure 6. This unit consists of two separate sub-assemblies. One sub-assembly contains the crystal clock which is used to generate a 10 megahertz time base. The time base is derived from a 50 megahertz crystal coupled to a "divide by 5" circuit which is reset at the start of each horizontal scanline. In this way, the starting point of the 10 megahertz time base can be more precisely aligned with the start of the horizontal scanline, thereby improving the accuracy with which pupil and corneal reflection intercept points may be determined.

The second sub-assembly contains all of the remaining circuitry that makes up this unit. It consists of a plug-in printed circuit board equipped with 39 integrated circuits and one transistor.

When a vertical synchronizing pulse comes from the camera, it clears the line count accumulator, indicating that a new field is about to be scanned by the camera. When this pulse is terminated by the camera, there is a time lag of a few microseconds prior to the occurrence of the first horizontal synchronizing pulse. As soon as the first horizontal synchronizing pulse is generated by the camera, it increments the line count accumulator and puts out an interrupt signal to the computer, telling the computer to interrupt whatever it is doing since the interface unit must be serviced. The total amount of time required to service the interface unit and to prepare the interface unit to monitor the next scanline is approximately 18 microseconds. Therefore the horizontal

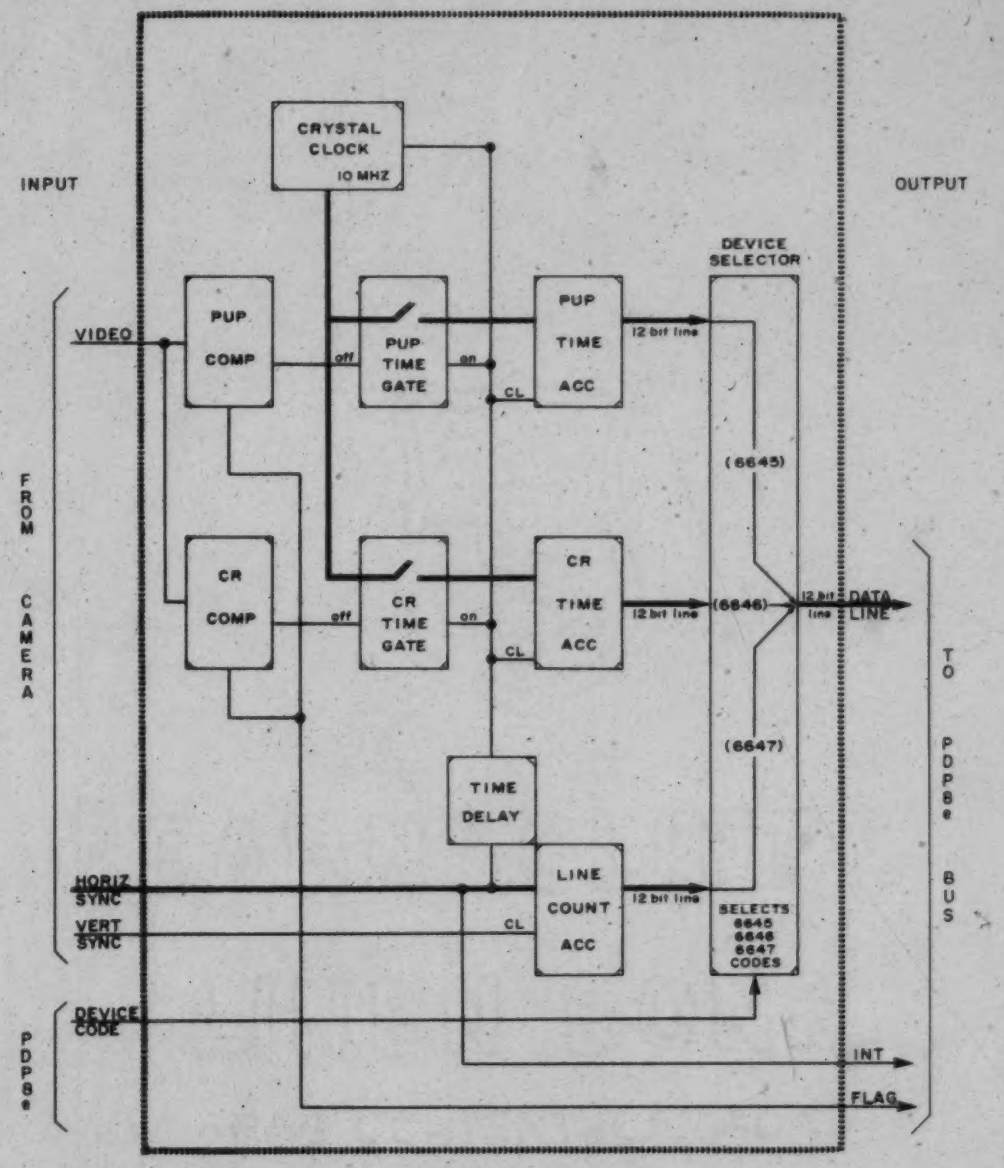


Figure 6

COMPUTER - CAMERA INTERFACE UNIT

simplified block schematic

LEGEND

ACC	*accumulator*
CL	*clear*
COMP	*comparator*
CR	*corneal reflection*
INT	*interupt*
PUP	*pupil*
VERT	*vertical*
HORIZ	*horizontal*
———	*primary signal path*

synchronizing pulse is also fed into a variable time delay circuit which is adjusted to 18 microseconds, and the output from the time delay circuit is used to initiate the operation of the interface unit to monitor the next scanline. Since the camera requires only 10.2 mirco-seconds to return the scanline to its starting position and begin scanning the next scanline and the interface unit requires 18 micro-seconds before it begins monitoring the next scanline, the scanline performs the first portion of its scan without being monitored by the interface unit. This occurs for a period of approximately 14% of the total horizontal scan width. Therefore, in positioning the subject before the oculometer, care must be taken to insure that the image of the eye does not fall within this (the leftmost) region.

To initiate the operation of the interface unit, the output pulse from the time delay circuit simultaneously clears the pupil time and CR time accumulators, turns on the pupil time gate and the CR time gate, and zeros the divide by 5 circuit on the crystal clock. This connects the crystal clock to the pupil time accumulator and the CR time accumulator so that these accumulators are incremented by the crystal clock by a count of one every tenth of a microsecond.

If the video signal from the camera is the result of scanning black background, the size of the video signal will be smaller than a preset threshold voltage level at the comparators. As a result, the comparators will not "fire", and the "flag" will not be raised. When the scan is completed, the next horizontal synchronizing pulse occurs, and the process is repeated.

If the video signal from the camera is the result of scanning the

pupil, the size of the video signal will be larger than the preset reference voltage level at the pupil comparator, but smaller than the preset reference voltage level at the CR comparator. This means that the instant that the pupil is intercepted the pupil comparator will "fire", turning off the pupil time gate and turning on the "flag", telling the computer that an increase in video signal has been located. At this time, the pupil time accumulator will contain a time measurement which is directly related to the abscissa, and the line count accumulator will contain a scan line number which is directly related to the ordinate of the point where the scan line intercepted the contour of the pupil.

If the video signal from the camera is the result of scanning the corneal reflection, the size of the video signal will be larger than the preset threshold voltage level at the CR comparator. This means that the instant that the corneal reflection is intercepted, the CR comparator will send a signal which will turn off the CR time gate and turn on the flag, telling the computer that an increase in video signal has been located. At this time, the CR time accumulator will contain the abscissa and the line count accumulator will contain the ordinate of that point on the corneal reflection.

The computer-camera interface therefore senses the contour of the semi-circumference of both the pupil and the corneal reflection. The abscissa of each point on the contour is recorded in terms of "clock pulses" where one clock pulse is one tenth of a microsecond. A better indication of the horizontal scale of measure may be attained by expressing this as a linear measure at the eye of a subject positioned

16 inches from the camera. A horizontal displacement of one clock pulse corresponds to a linear measure at the eye of the observer of approximately .0064 inches. The ordinate of each point in each array is measured in terms of "scan lines". A vertical displacement of one scan line corresponds to a linear displacement of approximately .0048 inches at the eye of the observer.

Figure 7 illustrates the overall time relationship of the signals on this unit relative to the camera output signals. A detailed schematic diagram of the computer-camera interface unit is provided in Appendix A.

The Computer

The computer portion of the infrared computer based oculometer system serves three major functions. First, it monitors the "flag" and stores the contents of the three accumulators on the computer-camera interface unit whenever the "flag" is raised. Second, when the coordinates of all the points on the contours of the pupil and the corneal reflection have been stored, the computer uses this information to calculate the displacement of the corneal reflection from the pupil center and the pupil dilation. Finally, the computer transfers a record of this information onto a 9-track magnetic computer tape. This process is repeated once every thirtieth of a second.

The computer unit will be described in terms of the hardware that constitutes this unit, the software or programming that makes it operational, and the output that comes directly from this unit.

The Computer Hardware

The central process computer used in this research was a rack-

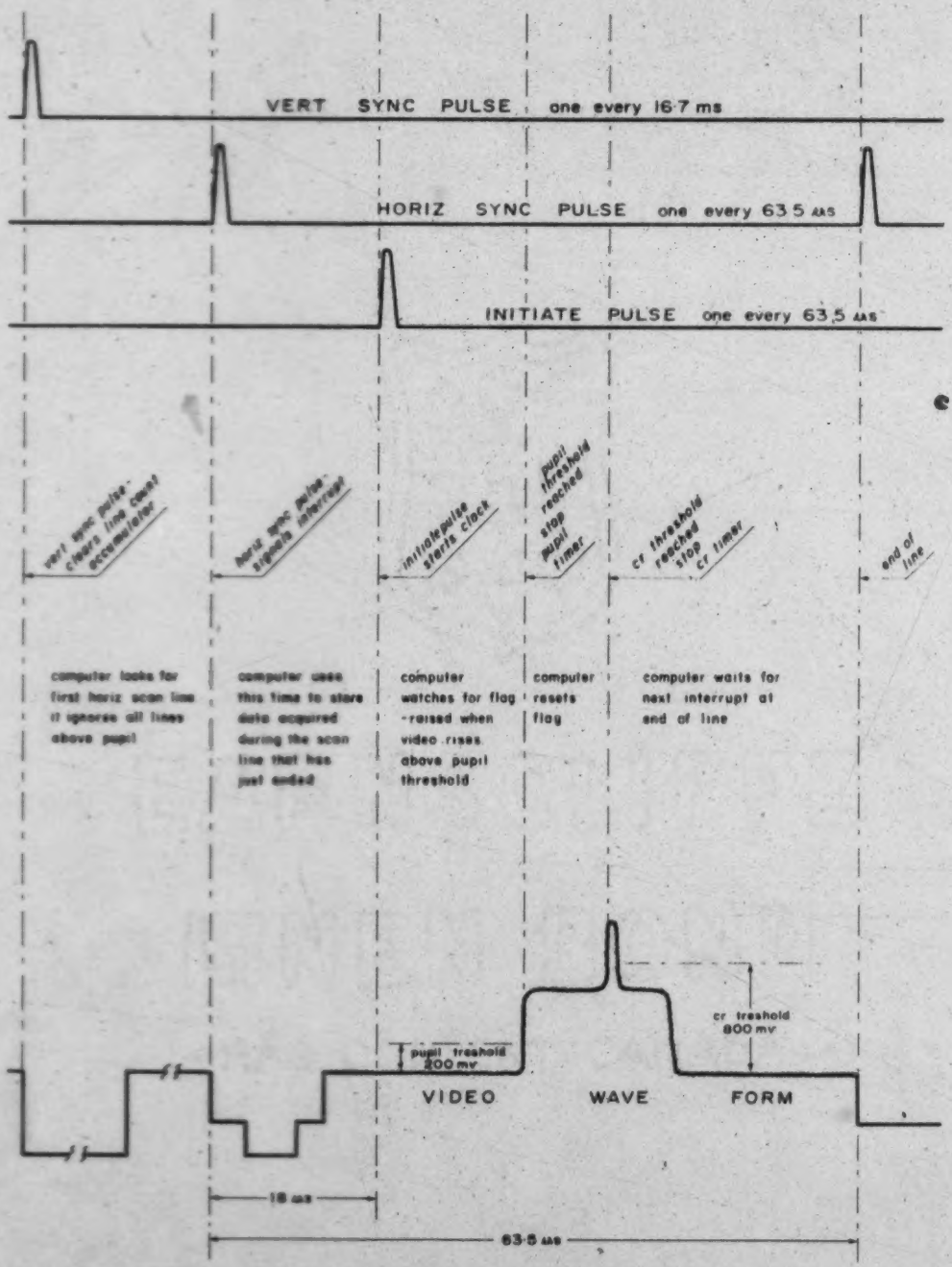

VERT SYNC PULSE one every 16.7 ms
HORIZ SYNC PULSE one every 63.5 µs
INITIATE PULSE one every 63.5 µs
vert sync pulse - clears line count accumulator
horiz sync pulse signals interrupt
initiate pulse starts clock
pupil threshold reached stop pupil timer
cr threshold reached stop cr timer
end of line
computer looks for first horiz scan line it ignores all lines above pupil
computer uses this time to store data acquired during the scan line that has just ended
computer watches for flag - raised when video rises above pupil threshold
computer resets flag
computer waits for next interrupt at end of line
cr treshold 800 mv
pupil treshold 200 mv
VIDEO WAVE FORM
18 µs
63.5 µs

Figure 7

RELATIONSHIP OF COMPUTER FUNCTIONS TO CAMERA OUTPUT SIGNALS

mounted model PDP-8/e minicomputer manufactured by Digital Equipment Corporation. It was equipped with 8K core, an extended arithmetic element, a two channel D/A converter, a one channel A/D converter, a power-fail and memory protect option, a 9-track magnetic tape unit and a model ASR33 teletype input/output unit. All of the above units were standard equipment supplied by Digital Equipment Corporation. In addition, a CONRAC video monitor, a Telequipment rack-mount oscilloscope and a 5-volt reference power source were also located on the rack. The computer-camera interface unit plugged directly into the bus of the computer.

Appendix B shows the configuration of the equipment on the rack. Appendix C shows a simplified block schematic of the computer hardware unit used in this study.

The Software

All of the programming for the infrared computer based oculometer system was done using machine language. While machine language programming tends to be the most tedious and time-consuming method of programming, it was selected for a number of reasons. First, most of the programming was completed before the magnetic tape unit arrived. This meant that the only way to load system programs such as the assembler was via paper tape and the teletype unit. This is an extremely slow and tedious process. Second, it was felt that more efficient programs could be written by programming in machine language. Finally, since the computer was acquiring information from the camera (via the interface unit) and processing it "on-line", it was more convenient during debugging to work in machine language. These factors, combined with the

fact that the overall program was relatively short, led to the decision to use machine language in programming the computer.

Essentially, the program is designed to store the contents of the three accumulators located on the computer camera interface unit whenever a scan line intercepts either the pupil and/or the corneal reflection, and to calculate and store the coordinates of the displacement of the corneal reflection from the pupil center, and the pupil dilation.

Two conditions are received by the computer from the computer camera interface unit; a "flag" that occurs whenever a scan line intercepts a pupil and/or a corneal reflection, and a "interrupt" that occurs whenever a scan line has reached the end of its scan. If during the early part of the scanning sequence, neither the pupil nor the corneal reflection are struck, the flag is not raised, and as each scan line reaches the end of its scan, an interrupt occurs. The absence of a flag means that there is no useful information, which needs to be stored, contained in the accumulators on the computer camera interface unit, so that immediately after the interrupt has occurred, normal program execution resumes as the next scan line begins. When a scan line strikes a pupil, the flag is raised. This means that the contents of two of the accumulators on the computer camera interface unit, namely the line count accumulator and the pupil time accumulator, need to be stored. The program therefore modifies itself so that immediately after the interrupt has occurred, the contents of these two accumulators are stored, and then normal program execution resumes, as the next scan line begins. This process is repeated until

a corneal reflection is struck. The program then again modifies itself so that after the interrupt occurs, all three of the accumulators on the computer camera interface unit are stored prior to resuming normal program execution. This process continues so that when the entire pupil has been scanned, the computer has stored the coordinates of every point on the semi-circumference of both the pupil and the corneal reflection.

During the time that the camera is scanning the dark portion of the image below the pupil, the computer calculates and stores the abscissa of the vertical tangents to the pupil and the corneal reflection, the pupil dilation, the diameter of the corneal reflection and the vertical displacement between the pupil center and the center of the corneal reflection. The dilation is measured and expressed in terms of the number of scan lines that actually intercepted the pupil. The ordinate of the pupil center is determined in terms of the absolute number of the scan line that pass through the pupil. This is determined by simply subtracting the absolute number of the first scan line that intercepted the pupil from the absolute number of the last scan line that intercepted the pupil and adding half this quantity to the absolute number of the first scan line that struck the pupil. (See Figure 8). For example, if the first scan line to strike the pupil was line 75 and the last scan line to strike the pupil was line 275, then the pupil dilation would be (275-75)=200 lines, and the ordinate of the pupil center would be located on line (75 + (275-75)/2)=175. The ordinate of the center of the corneal reflection is needed to

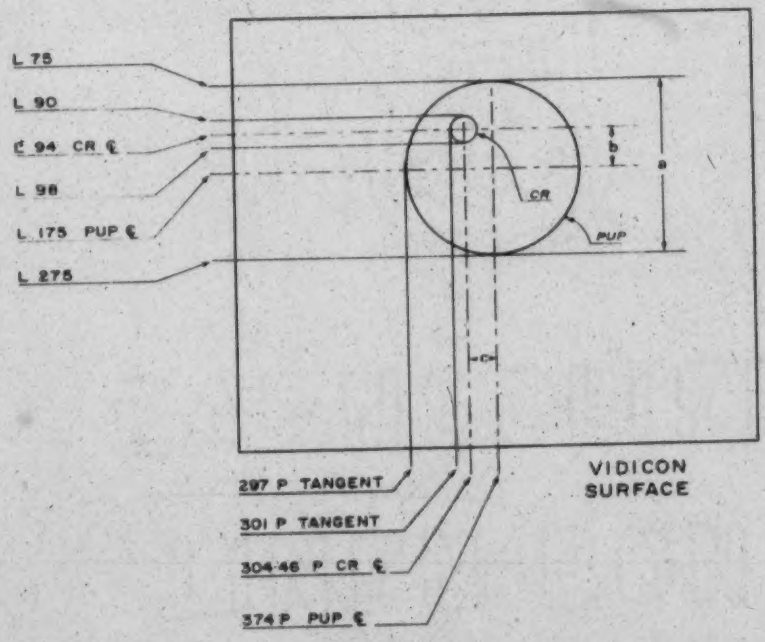


Figure 8

DERIVATION OF DILATION AND X- & Y- DISPLACEMENT

LEGEND

CR	*corneal reflection*
L	*line(s)*
P	*pulses*
PUP	*pupil*

determine the vertical coordinate of fixation, and is calculated in exactly the same way as the pupil center. Hence, if the first scan line that struck the corneal reflection was line 90, and the last one was line 98, then the center of the corneal reflection would be located on line (90 + (98-90)/2)=94. The vertical displacement of the center of the corneal reflection from the pupil center, which is a measure of the ordinate of fixation is simply calculated by subtraction, and in the example, is (175-94)=81 lines. Displacements occurring when the eye is looking up were labelled positive (+) and displacements occurring when the eye is looking down were labelled negative (-).

The abscissa of the pupil center and the horizontal displacement of the center of the corneal reflection with respect to the pupil center are calculated in terms of 10 megahertz clock pulses. As explained earlier in this chapter, a 10 megahertz clock begins incrementing the pupil time accumulator and the CR time accumulator at the instant that the scan line is initiated, and incrementing of each respective accumulators ceases when intercept of the pupil and/or the corneal reflection occurs.

To find the abscissa of the pupil center, the abscissa of the vertical tangent to the pupil is located first. The radius of the pupil is then calculated based on the measure of pupil dilation obtained previously. This abscissa of the pupil center is the sum of the abscissa of the vertical tangent to the pupil and the radius of the pupil.

The abscissa of the vertical tangent to the pupil is obtained by

calculating the mean horizontal displacement (observed over the four scan lines) nearest the center of the pupil. For example, in Figure 8, the center scan line of the pupil was line 175. The mean horizontal displacement of lines 174, 175, 176, and 177 would be used as the basis for determining the abscissa of the vertical tangent to the pupil. If the observed horizontal time displacements of lines 174-177 were 296, 297, 297 and 298 respectively, the abscissa of the vertical tangent to the pupil would be 297.

As explained previously, the dilation of the pupil is determined in terms of scan lines. Assuming that the pupil is circular, this measure of dilation may be expressed in terms of pulses by recognizing that the horizontal-to-vertical aspect ratio in a television system is 4:3, and that the vertical axis is scanned by 519 lines (consisting of 525 lines less 6 lines lost during retrace) and the horizontal axis consists of 533 pulses. The conversion factor for converting length measured in scan lines to pulses is (533/525 x 3/4) = 0.77. Therefore, the diameter of the pupil may be expressed in terms of pulses by multiplying the dilation in scan lines by 0.77. The radius is simply half the diameter. In the example in Figure 8, the pupil dilation of 200 lines is equivalent to (200 x .77) = 154 pulses so the radius of the pupil is 77 pulses. The abscissa of the pupil center is therefore (297 + 77) = 374 pulses.

The abscissa of the corneal reflection is calculated in a similar manner except that the mean abscissa to the vertical tangent is calculated over 3 lines. In Figure 8, the mean abscissa to the vertical tangent of the corneal reflection is 301 pulses, the radius of the corneal reflection is ((0.77 x 9) ÷ 2) = 3.46 and therefore the abscissa

of the corneal reflection center is 304.46 pulses.

The horizontal displacement of the center of the corneal reflection from the pupil center, which is a measure of the abscissa of fixation is simply calculated by subtraction and in the example is (374-304.46) = 69.54 pulses. Displacements occurring when the eye is looking to the left were labelled positive (+) and displacements occurring when the eye is looking to the right were labelled negative (-).

Upon completion of the calculations as described, the program stores the results in core memory. The computer then awaits the completion of the scan at which time a new scan is initiated, and the procedure is repeated. After each block of 180 sets of readings (6 seconds) is accumulated in core, the scanning procedure is interrupted for two thirtieths of a second while the readings are transferred to magnetic computer tape.

In the event that a complete scan takes place and no pupil is found, (as in the case of a blink), or no corneal reflection is found (as may occur when the subject looks away from the target at some extremely large angle), the program outputs a distinct set of characters (7777) in place of the displacement coordinates. This makes it possible to detect when "blinks" occurred and to determine the duration of the blinks.

The Output

Output from the infrared computer based oculometer is stored on 9 track magnetic tape. Included in the output are:

1. the abscissa of the vertical tangent to the pupil center expressed in terms of scan lines,
2. the abscissa of the vertical tangent to the corneal reflection expressed in terms of scan lines,
3. the ordinate of the displacement between the pupil center and the corneal reflection, expressed in terms of 10 megahertz clock pulses,
4. the pupil dilation expressed in terms of scan lines, and
5. the diameter of the corneal reflection, expressed in terms of scan lines.

This provides sufficient data for the calculation of the horizontal displacement between the pupil center and the center of the corneal reflection. The vertical displacement is available directly from the tape.

In order to express this data in terms of absolute target coordinates, it is necessary to calibrate the system to a particular subject. This is accomplished by having the subject look at several specific points in the target area whose physical locations relative to each other are known. By recording horizontal and vertical displacements of the corneal reflection relative to the pupil center for these points, prior to conducting the actual eye movement study, it is possible to express the displacements recorded by the oculometer in terms of physical location within the target area. The process of translating oculometer output coordinates into target coordinates along with other data analysis is carried out on the IBM 360 model 67 computer.

Proof of Performance

One problem that is an inherent part of the development of any new measuring instrument is the problem of establishing validity, reliability and accuracy, or proof of performance of the instrument. The infrared computer based oculometer is not unique in this respect. This section of the study will describe the method that was followed in establishing proof of performance of the system and will present proof of performance findings.

The task of determining where a subject is looking may be broken down into several sub-tasks. First, since changes in the displacement of the corneal reflection with respect to the center of the pupil are related to changes in eye pointing direction, one sub-task is to be able to accurately measure this displacement at any instant in time. This implies that the infrared computer based oculometer system must have the capability of measuring linear distances in both the horizontal and the vertical directions. The first part of the proof of performance will therefore be to establish the existence of this capability.

A second sub-task is to be able to determine the position of the centers of both the pupil and the corneal reflection, since these centers are not made directly readable by the illumination process. Possible sources of error with respect to the performance of this sub-task will be identified and their effect on the determination of where a subject is looking will be discussed.

A third sub-task is to be able to associate an observed displacement (of the corneal reflection with respect to the center of the pupil)

with the actual point in space being observed, taking into account both the error due to the oculometer system and error due to uncertainty about where the human eye is actually looking at a given instant in time. Determination of system performance on this sub-task will result in a statement of the system's limits of capability for determining where a subject is looking.

Measurement of Linear Displacement

In order to assess the capability of the infrared computer based oculometer system to measure horizontal and vertical linear displacements, a simulated eye was constructed. It consisted of a black box 3.5" x 4" x 2" deep. On the face of the box was a white circle 0.28 inches in diameter which contained a pinhole arbitrarily positioned in the lower right quadrant of the circle. A 5 watt, 110 volt incandescent lamp was mounted in the box, directly behind the pinhole. When positioned in the field of view of the camera, the image of the simulated eye very closely resembled the image of a human eye, the incandescent light behind the pinhole created an intense 'spot' resembling the corneal reflection, the white circle resembling the pupil, and the black background of the box resembling the face of the subject.

For testing purposes, the simulated eye was positioned in the field of view of the camera unit so that a properly focused image closely resembling the eye appeared on the video monitor. With an intensity setting of 40 on the variac, the camera produced a video output signal closely resembling that shown in solid lines in Figure 7.

The oculometer system was then started, resulting in the simulated eye being scanned over 100 consecutive frames, the results of each scan being stored in the core memory of the computer.

All 100 sets of readings taken were identical, demonstrating the reliability of the system. It was observed that a total of 58 scan lines in the horizontal plane struck the simulated pupil, which was 0.28 inches in diameter. This demonstrated that the approximate vertical resolution rate of the oculometer system is .0048 inches between two adjacent scan lines at the eye. Similarly, it was observed that the difference in horizontal output corresponding to the radius of the simulated pupil (.14 inches) was 22 pulses. This demonstrated that the approximate horizontal resolution rate of the system is .0064 inches between two adjacent pulses at the eye.

Establishing the validity of the oculometer system in relation to measurement of linear displacements was simply demonstrated by placing a lens cover over the camera unit. This resulted in output from the system signifying that a blink had occurred; that is, that the system was unable to locate either a pupil or a corneal reflection. No internal noise which could cause a false identification was evidenced in the electronics of the system.

Determining Centers of the Pupil and Corneal Reflection

Given that the oculometer system is capable of measuring linear displacements as indicated above, once the points between which the measurement must be made are established, it is necessary to consider possible ways in which error might be introduced in the determination of these points. Two types of error will be considered. Error

designated in this study as "type A" error occurs when a very small change in pupil diameter or corneal reflection diameter has occurred, while error designated in this study as "type B" error occurs because of the system's inability to resolve dimensions less than one scan line in the vertical plane and less than one clock pulse in the horizontal plane. The effects of each type of error will be considered separately for the vertical and for the horizontal directions.

For measurements in the vertical direction (measured in terms of scan lines) it will be assumed that a target positioned in the space between two adjacent scan lines will be measured to the nearest scan line. That is, if a target extends across lines 20, 21, 22, and beyond line 22, partially across the space between lines 22 and 23, it will be resolved as extending to line 22 if it extends less than half way between lines 22 and 23, and as extending to line 23 if it extends more than half way between lines 22 and 23.

To illustrate the possible effects of type A error on measurement, in the vertical direction, the following example will be considered. Assuming that a pupil was positioned precisely between and tangent to lines 122 and 196. (See Figure 9), simple calculations reveals that the center of the pupil would lie on line 159. Now suppose that the pupil were to remain stationary at this point, but were to undergo a slight dilation. Assuming that the dilation occurred symmetrically around line 159, the pupil might at some point in time extend one-third of the distance towards lines 121 and 197. This in itself would produce no change in the oculometer output. However, if coupled with this change in dilation, the subject were to raise his head by one-

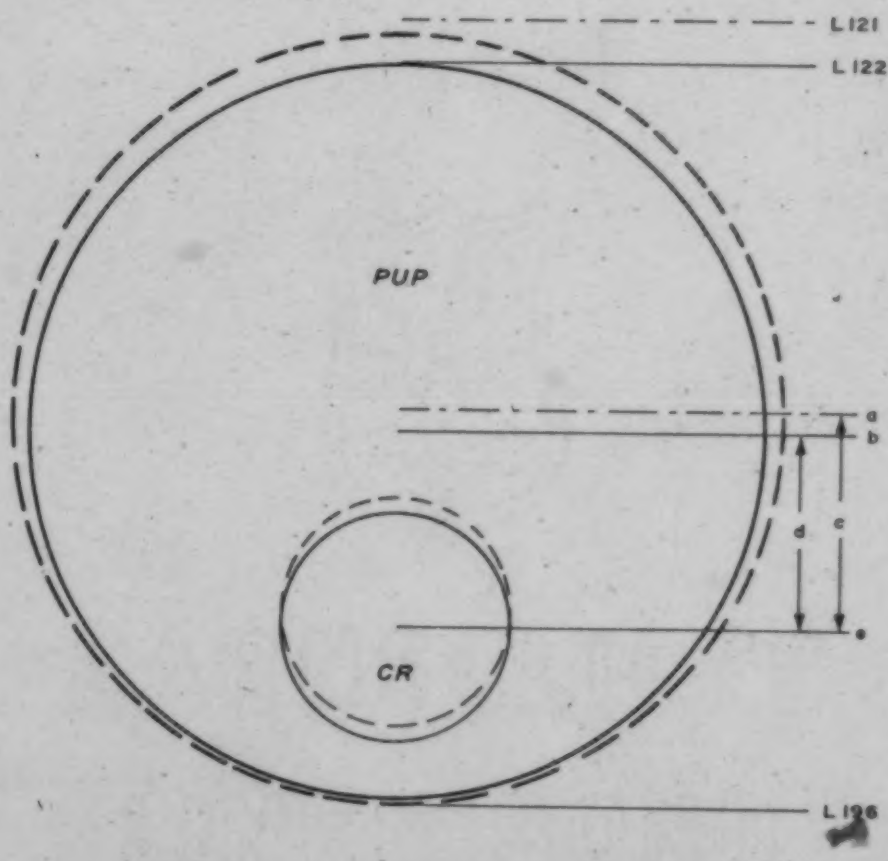


Figure 9

EFFECT OF "TYPE A" ERROR ON
MEASUREMENT OF VERTICAL DISPLACEMENT

third of a line, the combined effect of dilation and head movement would locate the top of the pupil more than half way toward line 121. The oculometer system would then consider the pupil to be positioned between lines 121 and 196 with its center lying midway between lines 158 and 159. Supposing that in the meantime, the corneal reflection had remained fixed, the oculometer output would show a change in vertical displacement of one-half line even though there was no change in eye pointing direction. Since this apparent movement of the pupil center could occur either upward or downward, the maximum expected variation in the position of the pupil center due to type A error is $\pm\frac{1}{2}$ line. The same phenomenon could occur in relation to the center of the corneal reflection, hence the maximum expected variation in the position of the corneal reflection center would also be $\pm\frac{1}{2}$ line. However, because movement of the pupil center (upward or downward) necessarily implies a corresponding movement of the corneal reflection center, it would not be expected that these two errors would be cumulative. Therefore, the maximum expected type A error for measurement of displacements in the vertical plane would be $\pm\frac{1}{2}$ scan line.

The possible effects of type B error on measurements in the vertical direction may be illustrated by again considering a pupil positioned precisely between and tangent to lines 122 and 196, whose centerline would be positioned on line 159 (see Figure 10). If there existed a corneal reflection within this pupil such that it was positioned precisely between and tangent to lines 169 and 179 with its center on line 174, the actual displacement between the two centers would be 15 lines, and the oculometer output would indicate this.

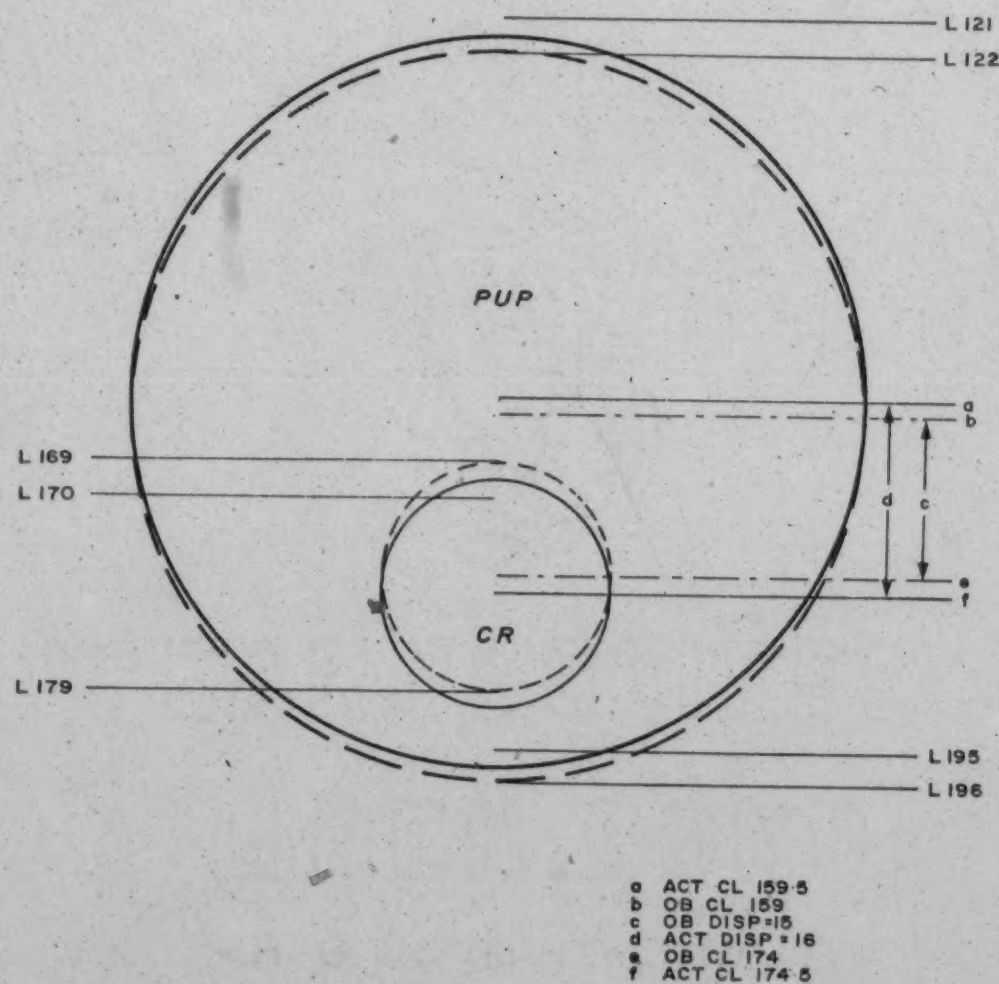


Figure 10

EFFECT OF "TYPE B" ERROR ON
MEASUREMENT OF VERTICAL DISPLACEMENT

However, it could also be possible that the entire pupil was positioned one-half line higher - just below the point that would cause lines 121 and 195 to resolve it. The pupil center would then actually be midway between lines 158 and 159 although the oculometer system would locate it on line 159. At the same instant the corneal reflection could be positioned on-half line lower - just above the point that would cause lines 170 and 180 to resolve it. The corneal reflection center would then actually be midway between lines 174 and 175, although the oculometer system would locate it on line 174. In this case, therefore, the actual displacement between the two centers would be 16 scan lines, but would be recorded by the oculometer system as 15 scan lines. In a similar manner, the pupil could be located as much as one-half line below lines 122 and 196 while the corneal reflection could be located as much as one-half line above lines 169 and 179. In this case, the oculometer system would still record the displacement between the two centers as 15 scan lines even though the actual displacement was only 14 scan lines. Therefore the maximum expected type B error for measurement of displacements in the vertical plane would be ±1 scan line.

For measurements in the horizontal plane, (measured in terms of 10 megahertz clock pulses) it will be assumed that a target positioned in space between two adjacent clock pulses will be measured in terms of the last complete clock pulse that intercepted the target. That is, if a target begins part way between pulse 22 and pulse 23, then it will be recorded as beginning at pulse 22, regardless of how near it exists to pulse 23.

To illustrate the possible effects of type A error or measurements in the horizontal plane, the following example will be considered. Supposing a pupil were positioned so that each of the four horizontal scan lines intercepted the vertical tangent to the pupil just as pulse 150 occurred (see Figure 11). Now, supposing that the pupil were to remain stationary at this point, but were to undergo a slight dilation. If the dilation was less than half a scan line the dilation reading recorded by the oculometer would remain unchanged. However, this slight dilation could be sufficient to cause the mean abscissa of the vertical tangent to the pupil to appear at pulse 149. As a result, an observed change in horizontal displacement equal to one pulse would be recorded by the oculometer when no actual change in eye pointing direction occurred (see Figure 11). Because only the leading edge (left edge) of the pupil circumference is sensed, type A error could only operate in a manner so as to decrease the true value of the horizontal position of the pupil center by one. A similar change could occur in the corneal reflection, resulting in a type A error in the position of the center of the corneal reflection, operating, as in the case of the pupil, to decrease the true value of the horizontal position of the center of the corneal reflection by one. The occurrence of both of these events simultaneously (since they both operate in the same direction) would result in cancellation of the error, therefore the maximum expected type A error for measurement of displacements in the horizontal plane would be -1 pulse.

The possible effects of type B error on measurements in the horizontal plane are illustrated in the example of Figure 12. Supposing

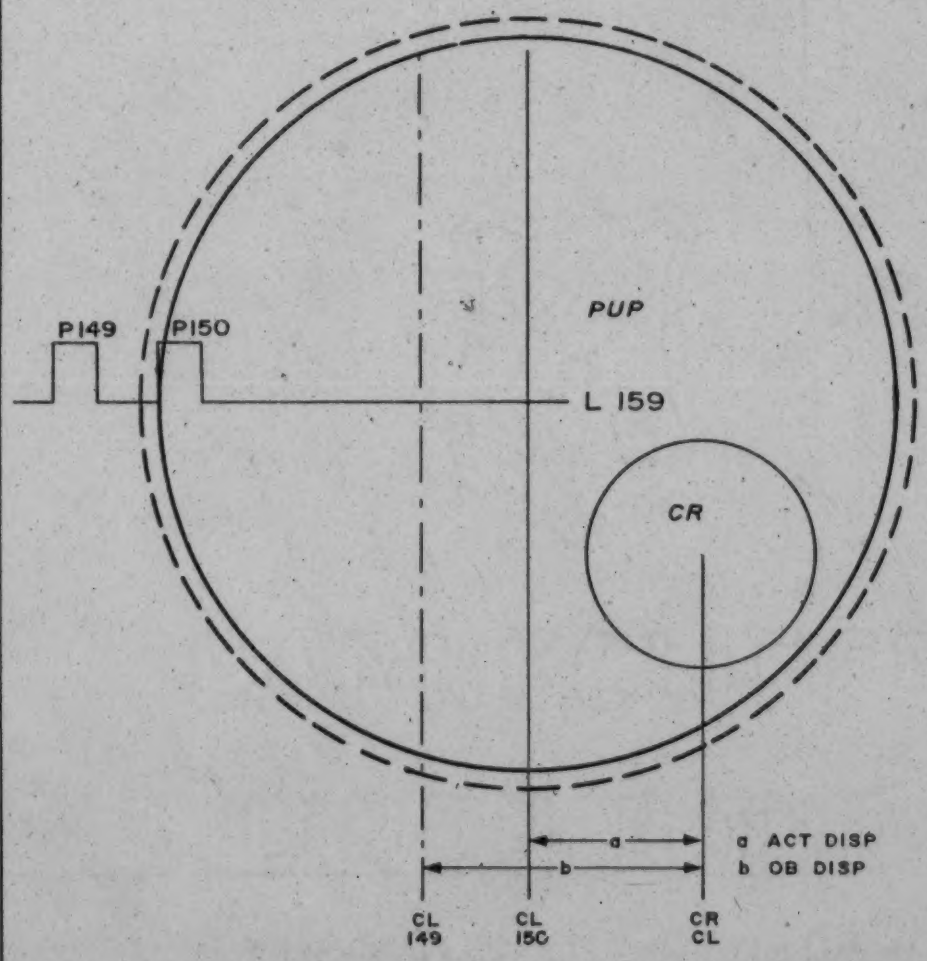


Figure 11

EFFECT OF "TYPE A" ERROR ON
MEASUREMENT OF HORIZONTAL DISPLACEMENT

a pupil were positioned so that each of the four horizontal scan lines intercepted the vertical tangent to the pupil just as pulse 150 occurred. Now supposing that the pupil were to move to a new position to the right (as shown by the broken lines of Figure 12) by an amount just less than one pulse. Because the movement would not be sufficient to change the observed position of the vertical tangent to the pupil the position of the pupil center would appear unchanged, even though a change of nearly one full pulse had occurred. Therefore the maximum expected variation in the position of the center of the pupil is -1 pulse. The possible effects of type B error on the determination of the horizontal position of the center of the corneal reflection are identical to those just described for the pupil, therefore, the maximum expected variation in the position of the center of the corneal reflection is also -1 pulse. The occurrence of both of these events simultaneously would result in cancellation of the error, therefore the maximum expected type B error for measurement of displacement in the horizontal plane is -1 pulse.

Actual System Performance

In order to assess the actual overall performance of the infrared computer based oculometer system, given the maximum expected errors of measurement for the system sub-tasks, a series of experiments involving both the simulated eye described earlier in this chapter and a human eye were carried out. The purpose of the experiments involving the simulated eye was to gather additional data to demonstrate the reliability and the validity of the oculometer system in a task

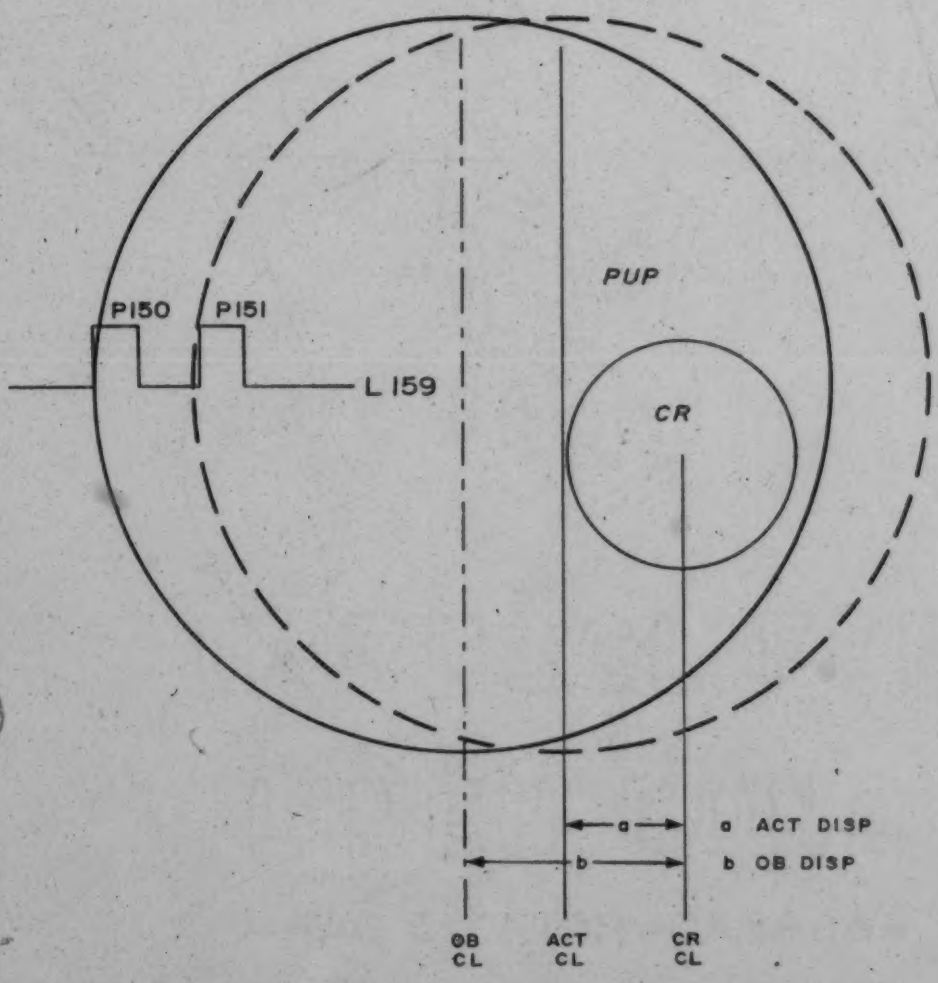


Figure 12

EFFECT OF "TYPE B" ERROR ON
MEASUREMENT OF HORIZONTAL DISPLACEMENT

involving the determination of the positions of the pupil center, corneal reflection center and pupil dilation, and the calculation of the horizontal and vertical displacements between the pupil center and the center of the corneal reflection for a stationary target. Because the normal human eye does not stay perfectly fixed, even when it is fixating on a stationary target oculometer output obtained from a human eye fixating a stationary target would include error resulting from normal movements of the eye inseparably combined with type A and type B errors. Therefore a statistical approach, presenting frequency distributions of oculometer system output for various tasks involving the human eye will be used to describe overall system performance.

In the second series of experiments, a simulated eye was positioned in the field of view of the camera unit of the oculometer. The video monitor was observed while the camera unit was adjusted to insure that it was properly focused. The intensity of the infrared light source was adjusted so that the video output voltage was as specified in Figure 8 (variac setting of approximately 50). The computer program included in appendix D was used but was modified to stop after 100 consecutive scans were completed. The output consisted of the coordinates of displacement between the pupil center and the center of the corneal reflection as well as pupil dilation. The observed measures of dilation and of displacement were 70 scan lines and 24.5 scan lines respectively. The variance of each of these was 0. The observed measures of X - displacement were normally

distributed around a mean of 7.69 pulses with a variance of 0.21. The experiment was repeated two more times, once with the "corneal reflection" pinhole blocked off so that no corneal reflection voltage was present, and a second time with the entire pupil covered by a piece of black construction paper. In both cases, the oculometer system output consisted of 100 identical readings, each denoting that a "blink" had been detected.

These experiments appear to strongly support both the validity and the reliability of the oculometer system. In the first case, identical readings obtained for measures of dilation and Y-displacement strongly suggests that the system provides a reliable measure for these parameters. The observed distribution of measures of X-displacement indicate the relatively high reliability with which the system measures this parameter. In the latter two cases, by eliminating portions of the simulated eye, it was demonstrated that the oculometer output changed appropriately, which suggests that the output from the oculometer system is a valid measure of displacement between the pupil center and the center of the corneal reflection.

In the third series of experiments, an IBM 1500 video terminal was positioned adjacent to the oculometer as shown in Figure 2. A Biometrics model 115 head restraint was positioned in front of the video terminal, so that the eye of a subject whose head was positioned in the chinrest of the head restraint would be 16 inches away from the screen of the video terminal. With a subject positioned in the head restraint, the video monitor was observed while the camera unit was adjusted to insure that it was properly focused. The intensity of the

infrared light source was adjusted so that the video output voltage was as specified in Figure 8 (variac setting of 45 to 50 depending on the subject. In various experiments that followed, a target consisting of an asterisk (*) was displayed in a variety of known coordinate locations on the video terminal. Because the movements of the eye are more steady when it is pursuing a smoothly moving object (Yarbus, 1967) the IBM 1500 CAI system was programmed to display a "moving asterisk". For experiments involving vertical displacements, the asterisk was programmed to move back and forth in a pendular fashion horizontally across five columns in specific rows, pausing for 300 milliseconds in each column. For experiments involving horizontal displacements, the asterisk was programmed to move up and down in a similar fashion, across five rows in specific columns, pausing for 300 milliseconds in each row. The subject was instructed to look at the asterisk. For each trial, 100 consecutive oculometer readings were taken. Table 1 is a summary of the displacements observed for one subject under different display conditions.

The mean vertical output displacement between the corneal reflection center and the pupil center was 20.15 scan lines while the subject was looking at the top row of the display and 5.44 scan lines while the subject was looking at the bottom row of the display. This represents a change of 14.71 scan lines resulting from a change in fixation of 4.6 inches, the distance between the top and bottom rows of the display. This means that a change in the point of fixation of .16 inches would result in a change in the vertical displacement output of 0.5 scan line. That is, neglecting error, the oculometer would be

TABLE 1

Oculometer Output for

Various Target Locations

Location of Asterisk		Mean Oculometer Output Displacement			
Horizontal Coordinates	Vertical Coordinates	Horizontal Pulses - Variance		Vertical Lines - Variance	
0	17-21			20.15	0.11
30	17-21			5.44	0.13
13-17	0	14.52	0.43		
13-17	39	-7.32	0.45		

N = 100 Readings

capable of detecting vertical changes in eye fixation greater than 0.16 inches on a display positioned 16 inches from the eye of the subject. This corresponds to an angular displacement of 0.6 degrees.

It has already been pointed out that for measurements in the vertical plane, the maximum expected type A error was ±½ scan line and the maximum expected type B error was ±1 scan line. Table 1 shows that the greatest variance of the observed vertical output displacements for the subject tested was .13. This corresponds to a standard deviation of less than 0.4. Because of the possibility of ±½ scan line of error associated with any given reading, and because ½ scan line has been found to correspond to .16 inches at a display 16 inches away from the eye, a given vertical displacement output coordinate defines a region .32 inches high which contains the point on the screen being fixated. Fixations within a region of .32 inches or 1.2 degrees may not be distinguished from each other. In order to distinguish between two points fixated on a display 16 inches from the eye, using the vertical displacement oculometer output, the two points must be separated vertically by more than .32 inches (1.2 degrees).

The mean horizontal output displacement between the corneal reflection center and the pupil center was 14.52 pulses while the subject was looking at the right edge of the display and -7.32 pulses while the subject was looking at the left edge of the display. This represents a change in horizontal displacement output of 21.84 pulses, resulting from a change in fixation of 7.9 inches, the distance between the left and right edges of the display. This means that a change

in the point of fixation of 0.18 inches would result in a change of 0.5 pulse in the oculometer horizontal displacement output. That is, neglecting error, the oculometer system would be capable of detecting horizontal changes in eye fixation greater than .18 inches on a display 16 inches away from the eye. This corresponds to an angular displacement of about 0.65 degrees.

As in the measurement of vertical displacement discussed earlier, because of this error, it is only possible to define a region which is 0.36 inches wide which contains a point on the display being fixated. Fixations within a region 0.36 inches wide or 1.30 degrees may not be distinguished from each other. In order to distinguish between two points fixated on a display 16 inches from the eye of a subject, using the horizontal displacement oculometer output, the two points must be separated by more than 0.36 inches (1.30 degrees).

In order to assess the linearity of the infrared computer based oculometer system, the numbers one to nine and the letters A and B were sequentially displayed at known coordinate locations of the screen of an IBM 1500 video terminal (see Figure 13). Each character appeared on the screen for exactly six seconds. The subject was positioned in front of the screen as previously described and was instructed to fixate each character as it appeared. Figure 13 shows the positions of the digits on the screen. Of the 180 readings obtained for each point fixated, the first thirty were rejected to insure that the eye had completed its saccade from the previous point being fixated. The next 60 readings were kept for analysis. The last 90 readings were not used since there is some evidence in

FIGURE 13

Calibration Stimuli

the literature that as the length of time spent fixating an object increases, the size of the drifts away from the point of fixation will also increase.

In order to calibrate the system, the mean observed X - coordinate for points six and A of the display was taken to be the X-distance between point six and A - two points which were three inches apart was used to establish a measure of the vertical resolution. Similarly the mean observed Y-coordinates for points seven and eight of the display was taken to be the Y-displacement for fixations on rows 18 and 19 of the screen and the distance between points seven and 8 - two points which were exactly four inches apart was used to establish a measure of the horizontal resolution. Table 2 shows a summary of calibration data obtained in this manner.

Based on the calibration data of Table 2 and the known locations of the calibration points on the screen, expected coordinate values for each of the eleven calibration points were calculated and compared to the observed coordinate values. Table 3 shows the comparison of expected and observed coordinates for the calibration points.

As indicated in Table 2, the vertical resolution of the system was 3.14 scan lines per inch at the screen of the video display. Since each character displayed on the screen was 0.3 inches high, this represents 0.94 scanlines. Similarly since the horizontal resolution was 2.46 pulses per inch, and each character displayed was 0.2 inches wide, this represents 0.49 pulses per character. Relating this to the error scores in table 3, one Y-displacement (the character B) and nine

TABLE 2

X and Y Calibration Data

Stimulus	Column	Row	Mean Observed X-Displacement	Mean Observed Y-Displacement
6	19	8 and 9	3.34	15.81
A	19	28 and 29	4.66	6.38
Mean			4.00	
Vertical Resolution Scan Lines per Inch				3.14
7	9	18 and 19	8.25	10.73
8	29	18 and 19	-1.59	10.90
Mean				10.82
Horizontal Resolution Pulses per Inch			2.46	

X-Displacement measured in terms of pulses

Y-Displacement measured in terms of scanlines

TABLE 3

X and Y Linearity Errors

Stimulus	Row	Column	Expected X-Disp.	Observed X-Disp.	X-Error	Expected Y-Disp.	Observed Y-Disp.	Y-Error
1	0 and 1	1	13.35	13.52	.17	19.36	19.94	.64
2	0 and 1	9	8.92	8.65	.27	19.30	20.22	.92
3	0 and 1	19	4.00	3.25	.75	19.30	20.13	.83
4	0 and 1	29	-0.92	-3.62	2.70	19.30	19.97	.67
5	0 and 1	37	-5.84	-8.13	2.29	19.30	18.82	.48
6	8 and 9	19	4.00	3.34	.66	15.53	15.81	.28
7	18 and 19	9	8.92	8.25	.67	10.82	10.73	.09
8	18 and 19	29	-0.92	-1.59	.67	10.82	10.90	.08
9	28 and 29	6	13.35	15.52	2.17	6.11	6.09	.02
A	28 and 29	19	4.00	4.66	.66	6.11	6.38	.27
B	28 and 29	39	-5.84	-6.51	0.67	6.11	4.92	1.19

X-Displacements measured in terms of pulses

Y-Displacements measured in terms of scanlines

X-displacement readings (the characters 3-9, A and B) had error scores greater than the size of a character. Only three characters (4, 5 and 9) had an X-error greater than two characters.

Since the angular displacement of the top row and the left edge both exceed 12 ½ degrees, and since earlier studies have suggested that the corneal reflection method is only linear for displacements of less than 12 ½ degrees, these errors can probably be attributed to non-linearity. However, since the remainder of the observed errors are small in relation to the size of the target being fixated, they will be considered negligible for the purposes of this study.

Summary

This chapter describes the infrared computer based oculometer system developed for recording eye movements of subjects involved in various learning tasks. It also provides details on proof of performance of the system. The following chapter will deal with the application of the infrared oculometer system. It will describe the conditions under which eye movements of subjects were recorded during some learning tasks and will present the findings.

CHAPTER IV

DESCRIPTION OF TESTING AND PRESENTATION OF FINDINGS

Introduction

Knowing where a subject is looking under given stimulus conditions is important to many different fields of research. In education, it is particularly important, because failure of stimuli to elicit a visual response from the learner can often inhibit learning. Knowing how the learner responds to a visual stimulus can provide the instructor with feedback, making it possible for him to modify stimulus material in order to elicit the desired visual response from the learner.

This study describes and documents the development of an infrared computer based oculometer which would provide a means for determining where subjects are looking when presented with visual stimuli. This chapter describes how three subjects' eye movements were recorded while they were viewing visual stimuli presented to them in a simulated learning situation. It also presents the analysis of these eye movements.

Procedure

The stimulus materials used in this study were presented to subjects via a video computer terminal connected to the IBM 1500 computer assisted instruction system in the Division of Educational Research Services of the University of Alberta. A total of five

stimulus situations were presented to each of three subjects. The first stimulus situation consisted of the numbers one to nine and the letters A and B as described in chapter three and illustrated in Figure 13. The purpose of this stimulus situation was to obtain data for each subject that would permit calibration of the system to the subject.

The second, third and fourth stimulus situations are shown in Figures 14, 15 and 16 respectively. These stimulus situations were frames of material selected from a course in inferential statistics developed for use with the IBM 1500 CAI system. One word was deliberately spelled incorrectly in stimulus situation 1 and was intended to provide a calibration check at the end of the testing sequence.

The subjects were all mature adults (two male and one female) and all were familiar with elementary statistical terms and concepts and all were familiar with the video terminal. Each subject was positioned in an adjustable chair at a desk on which was located the IBM 1500 video terminal and adjacent to it, the Honeywell optical head. The general testing procedure was explained to the subject, then the subject's head was positioned in the headrest and the chair and headrest were adjusted until a clear, well focused image of the pupil and corneal reflection were visible on the video monitor. The subject was asked to look at various locations on the display while the intensity of the infrared source was adjusted. Finally, the computer was started and the presentation of visual stimuli was

SIMPLE STATISTICS MAY BE USED TØ EST-
IMATE PØPULATIØN PARAMETERS WHEN IT IS
NØT PØSSIBLE TØ MEASURE A PARTICULAR
CHARACTERISTIC IN THE PØPULATIØN. AN
ØBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ØNE ØF A LAARGE NUMBER ØF
PØSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDØM SAMPLING DISTRIBUTIØN ØF MEANS.

FIGURE 14

Stimulus Situation 2

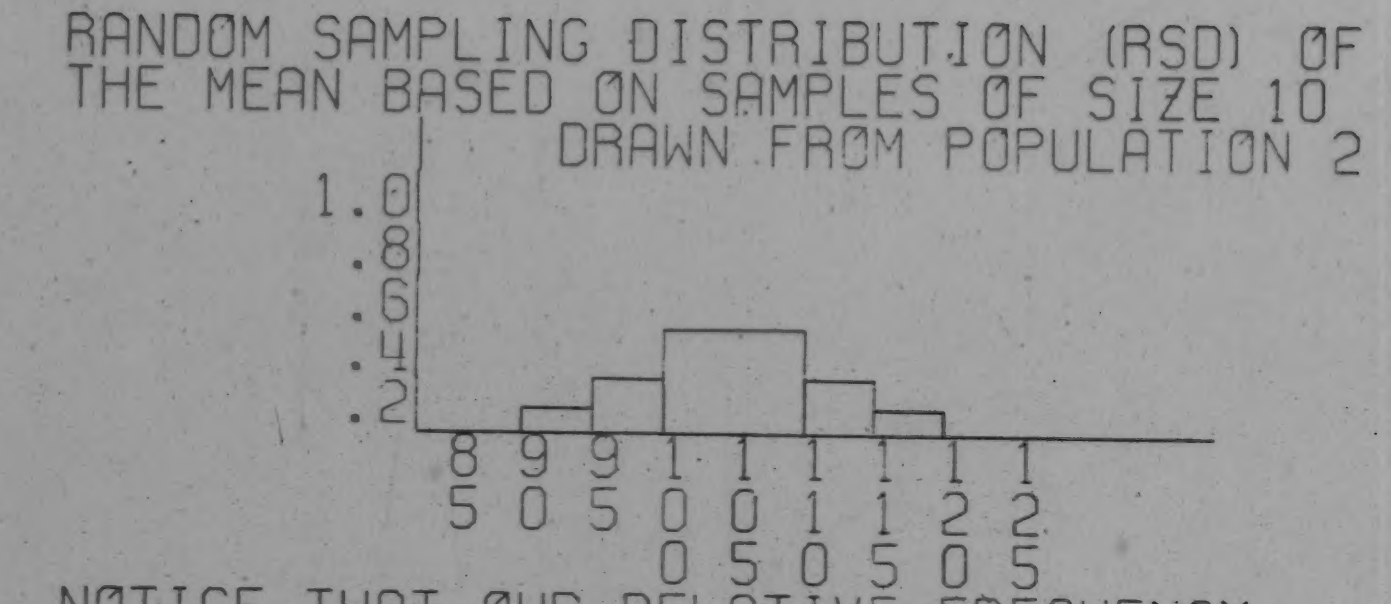
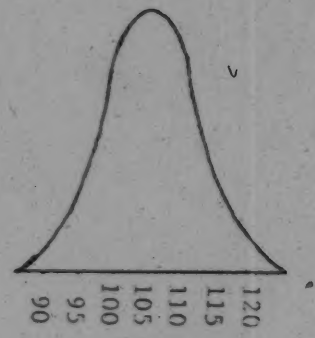

RANDOM SAMPLING DISTRIBUTION (RSD) OF
THE MEAN BASED ON SAMPLES OF SIZE 10
DRAWN FROM POPULATION 2
1.0
.8
.6
.4
.2
8 9 9 1 1 1 1 1 1
5 0 5 0 0 1 1 2 2
0 5 0 5 0 5
NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR. . .

FIGURE 15

Stimulus Situation 3

RANDOM SAMPLING DISTRIBUTION
OF THE MEAN BASED ON
SAMPLES OF SIZE 10 DRAWN
FROM POPULATION 2



WHAT IS THE MEAN OF THIS RSD?

0 95 0 105 0 115

FIGURE 16

Stimulus Situation 4

initiated by the researcher. Stimulus situation 1 presented the subject with the numbers one to nine and letters A and B sequentially, each character being displayed for six seconds. At the end of stimulus situation 1, stimulus situation 2 was automatically presented and was kept on the screen for 20 seconds. This was sufficient time for all subjects to finish reading this frame, which, as may be seen from figure 14, consisted of eight lines of text. After 20 seconds, stimulus situation 3 was automatically presented. This stimulus situation consisted of some text combined with a figure depicting a histogram as shown in Figure 15. The subject was required to press the space bar in order to go on to the next stimulus situation. Stimulus situation four consisted of some text and a graph. The text asked a question, such that the subject would have to view the graph, then view three possible answers to the question. The subject was instructed to simply think of the right answer - he was not required to give a response other than a visual response. After 20 seconds, the last stimulus situation, which consisted of the calibration stimuli used in stimulus 1 was automatically presented.

At the end of the testing sequence, the magnetic tape containing the data was removed and delivered to the IBM 360 system for analysis. A number of programs were written in Fortran to analyze the data contained on the tape. While in this study, a separate tape was made up containing data for each subject, this, in general would not be necessary since the oculometer system is capable of registering an "end-of-file" mark on the tape. This would insure that each subjects'

data would be kept separate.

Analysis

Stimulus Situation 1 - Calibration

The analysis of the data consisted of calculating the X-displacement for each set of readings recorded, summarizing the data, scaling the data to linear dimensions corresponding to the size of the display screen and plotting the data, superimposed on the appropriate text. Each analysis of eye movements will be presented separately for each subject.

Table 4 presents a summary of the calibration data obtained for each of the three subjects when they were viewing stimulus situation 1 (see Figure 13). To calibrate the system to each individual, a set of imaginary axis running vertically between points six and A and horizontally between points 7 and 8 were established. These points were selected because they were approximately in the center of the display screen. In this manner, the angular displacement of the eye while fixating these points would likely be small enough so as not to introduce error due to non-linearity (12 ½ degrees).

The position of the mean X-calibration axis, the imaginary vertical line between points 6 and A was determined by calculating the average of the mean observed X-displacements recorded for a period of two seconds (60 readings) for points 6 and A. For example, the mean X-calibration axis for subject one (table 4) was 0.99. This means that the estimate of the X-displacement between the pupil center and the corneal reflection for subject 1, when he was fixating points on a

vertical axis joining points 6 and A was +0.99. Similarly, the position of the mean Y-calibration axis, the imaginary horizontal line between points 7 and 8 was determined by calculating the average of the mean observed Y-displacements recorded for a period of two seconds (60 readings) for points 7 and 8. For example, the mean Y-calibration axis for subject 1 (Table 4) was 10.09. This means that the estimate of the Y-displacement between the pupil center and the corneal reflection for subject 1, when he was fixating points on a horizontal axis joining points 7 and 8 was 10.09.

The horizontal resolution for each subject was estimated by dividing the difference between the mean observed X-displacement for points 7 and 8 by the physical distance between these points on the display screen (4 inches), and was expressed in pulses per inch. For example, the mean observed X-displacement for subject one (Table 4) while fixating point 7 was 5.77 pulses while the mean observed X-displacement for this subject while fixating point 8 was -3.98 pulses. The change in X-displacement as the subject changed his point of fixation from point 7 to point 8 was (5.77 - (-3.980) = 9.75 pulses. Since these points were four inches apart on the display screen, the horizontal resolution for subject one was (9.75 ÷ 4) = 2.44 pulses per inch. This meant that assuming a linear relationship between the displacement of the corneal reflection from the pupil center and the corresponding change in the horizontal position of the point being fixated, for every inch that the point of fixation moved on the display screen, the observed X-coordinate of the displacement of the corneal reflection from the pupil center changed by 2.44 pulses.

TABLE 4

X and Y Calibration Data

Subject	Stimulus	Mean Obs. X-Disp.	Mean X Calib. Axis	Horizontal Resolution	Mean Obs. Y-Disp.	Mean X Calib. Axis	Vertical Resolution
	6	.61			15.50		
1	A	1.37	0.99	2.44	4.47		
	7	5.77			10.06		
	8	-3.98			10.12	10.09	3.68
	6	9.76			18.10		
2	A	10.26	10.01	2.82	6.37		
	7	15.69			12.12		
	8	4.40			12.13	12.12	3.91
	6	0.05			14.52		
3	A	1.01	.53	2.02	4.47		
	7	4.58*			9.63*		
	8	-3.52			9.63	9.63	3.35

*Estimated Displacements.

The vertical resolution for each subject was estimated similarly except that the mean observed vertical displacements for points 6 and A (located three inches apart on the display screen) were used to estimate it. Also since vertical displacement was measured in terms of scan lines, the vertical resolution was expressed in terms of scan lines per inch.

Given the X- and Y- calibration data for a subject, it is possible to calculate the expected values of X- and Y- displacement between the corneal reflection and the pupil center for any point on the display screen. For example, supposing subject one were fixating a point that was one inch above the horizontal calibration axis (points 7 and 8) and one inch to the left of the vertical calibration axis (points 6 and A). Since his horizontal resolution rate was 2.44 pulses per inch, the expected X-displacement between the corneal reflection and the pupil center would be 2.44 pulses greater than it was when the subject was fixating the vertical axis or (0.99 + 2.44) = 3.43 pulses. Similarly, since his vertical resolution rate was 3.68 lines per inch, the expected Y-displacement between the corneal reflection and the pupil center would be 3.68 lines greater than it was when the subject was fixating the horizontal axis or (10.09 + 3.68) = 13.77 lines. Conversely, given a set of X- and Y- displacement coordinates and the calibration data, one can estimate the point on the display screen (with reference to the horizontal and vertical calibration axes) that the subject was fixating.

In order to assess the possible error that was inherent in this method of estimating eye pointing direction, expected X- and Y-

coordinates were calculated for each of the calibration points. Observed mean displacement coordinates were subtracted from expected coordinates in order to estimate the error. Tables 5 - 7 show the error scores and Figures 17 - 19 show the plots of the calibration points as they appeared on the display screen together with the plots of calculated eye pointing position for each of subjects 1, 2 and 3 respectively.

Subject 1 had a total of 5 calibration points that were more than one character width away from the calculated position in the horizontal plane and two points that were more than one character height away from the calculated position in the vertical plane. Subjects two and three had three and seven (respectively) calibration points that were more than one character width away from the calculated position in the horizontal plane and two points that were more than one character height away from the calculated position in the vertical plane. Subject two and three had three and seven (respectively) calibration points that were more than one character width away from the calculated position in the horizontal plane and one and no points more than one character height away from the calculated position in the vertical plane. Figures 17 - 19 show the uncorrected plots of the observed eye pointing position relative to the position of the calibration points for each subject.

Conclusions

In view of the fact that previous studies have reported that the corneal reflection method of calculating eye pointing coordinates was not linear beyond 12 ½ degrees of displacement, and in view of the

TABLE 5

Error Table for Subject 1

Calib. Point	Expected X-Disp.	Observed X-Disp.	X Error	Expected Y-Disp.	Observed Y-Disp.	Y Error
1	10.26	8.68	1.58*	20.02	19.03	.99
2	5.87	4.06	1.81*	20.02	19.31	.71
3	.99	0.44	.55*	20.02	19.31	.71
4	-3.89	-4.41	.52*	20.02	19.42	.60
5	-8.77	-8.83	.04	20.02	18.69	1.33*
6	0.99	.61	.38	15.61	15.50	.11
7	5.87	5.77	.10	10.09	10.06	.03
8	-3.89	-3.98	.09	10.09	10.12	.03
9	10.26	10.32	.06	4.57	3.96	.62
A	0.99	1.37	.38	4.57	4.47	.10
B	-8.77	-7.01	1.76*	4.57	2.64	1.93*

*Denotes errors greater than one character in size.

TABLE 6

Error Table for Subject 2

Calib. Point	Expected X-Disp.	Observed X-Disp.	X Error	Expected Y-Disp.	Observed Y-Disp.	Y Error
1	20.73	20.04	.69*	22.68	21.71	.97
2	15.65	14.18	1.47*	22.68	21.72	.96
3	10.01	8.61	1.40*	22.68	22.18	.50
4	4.37	4.81	.44	22.68	22.34	.34
5	-1.27	-1.15	.12	22.68	21.47	1.21*
6	10.01	9.76	.25	17.99	18.10	.11
7	15.65	15.69	.04	12.13	12.12	.01
8	4.37	4.40	.03	12.13	12.13	.00
9	20.73	21.29	.56	6.26	5.77	.49
A	10.01	10.26	.25	6.26	6.37	.11
B	-1.27	-1.49	.22	6.26	6.02	.24

*Denotes errors greater than one character in size.

TABLE 7

Error Table for Subject 3

Calib. Point	Expected X-Disp.	Observed X-Disp.	X Error	Expected Y-Disp.	Observed Y-Disp.	Y Error
1	8.21	6.73	1.48*	18.68	17.72	.96
2	4.57	3.05	1.52*	18.68	18.70	.02
3	0.53	-1.58	1.05*	18.68	18.95	.27
4	-3.51	-4.93	1.42*	18.68	18.93	.25
5	-7.55	-9.24	1.69*	18.68	17.84	.84
6	0.53	.46	0.07	14.66	14.52	.14
7	4.57	**		9.56	**	
8	-3.51	-3.52	.01	9.56	9.63	.07
9	8.21	**		4.61	**	
A	0.53	1.01	.48*	4.61	4.47	.14
B	-7.55	-8.76	1.21*	4.61	3.89	.72

*Denotes errors greater than one character in size.

**Denotes missing data.

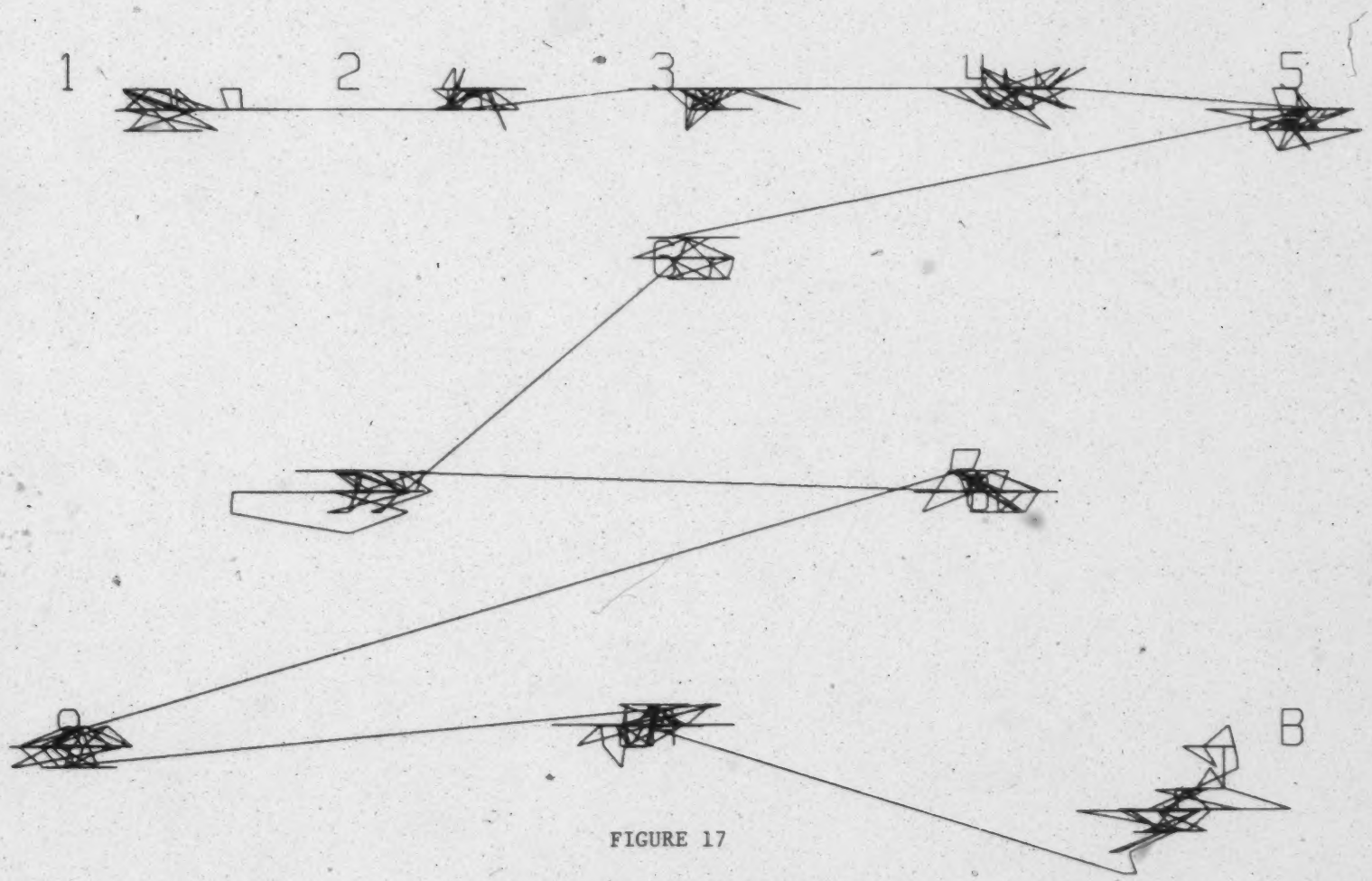


FIGURE 17

Uncorrected Eye Pointing
Positions For Subject 1
Viewing Stimulus Situation 1

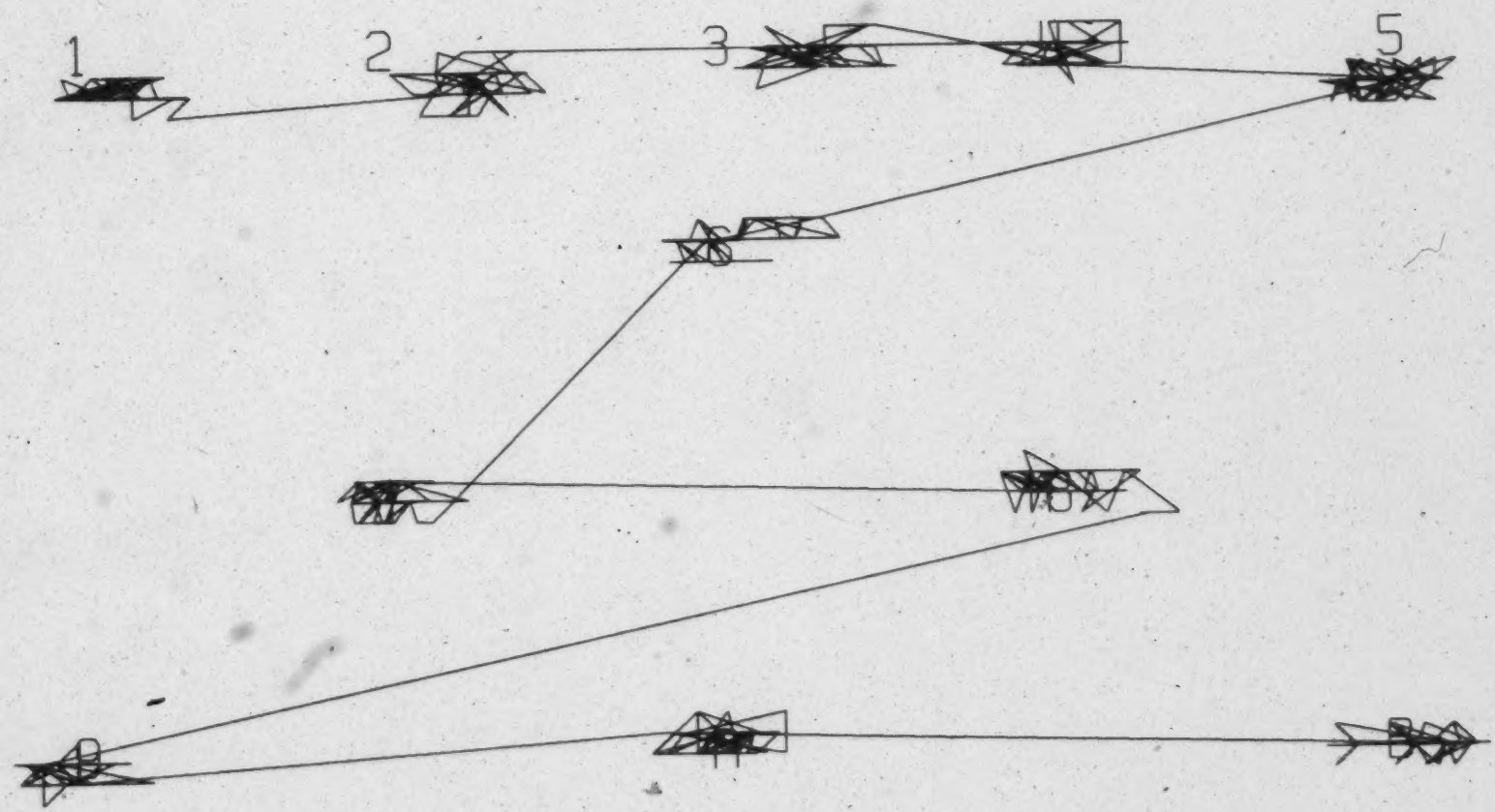


FIGURE 18

Uncorrected Eye Pointing
Positions for Subject 2
Viewing Stimulus Situation 1

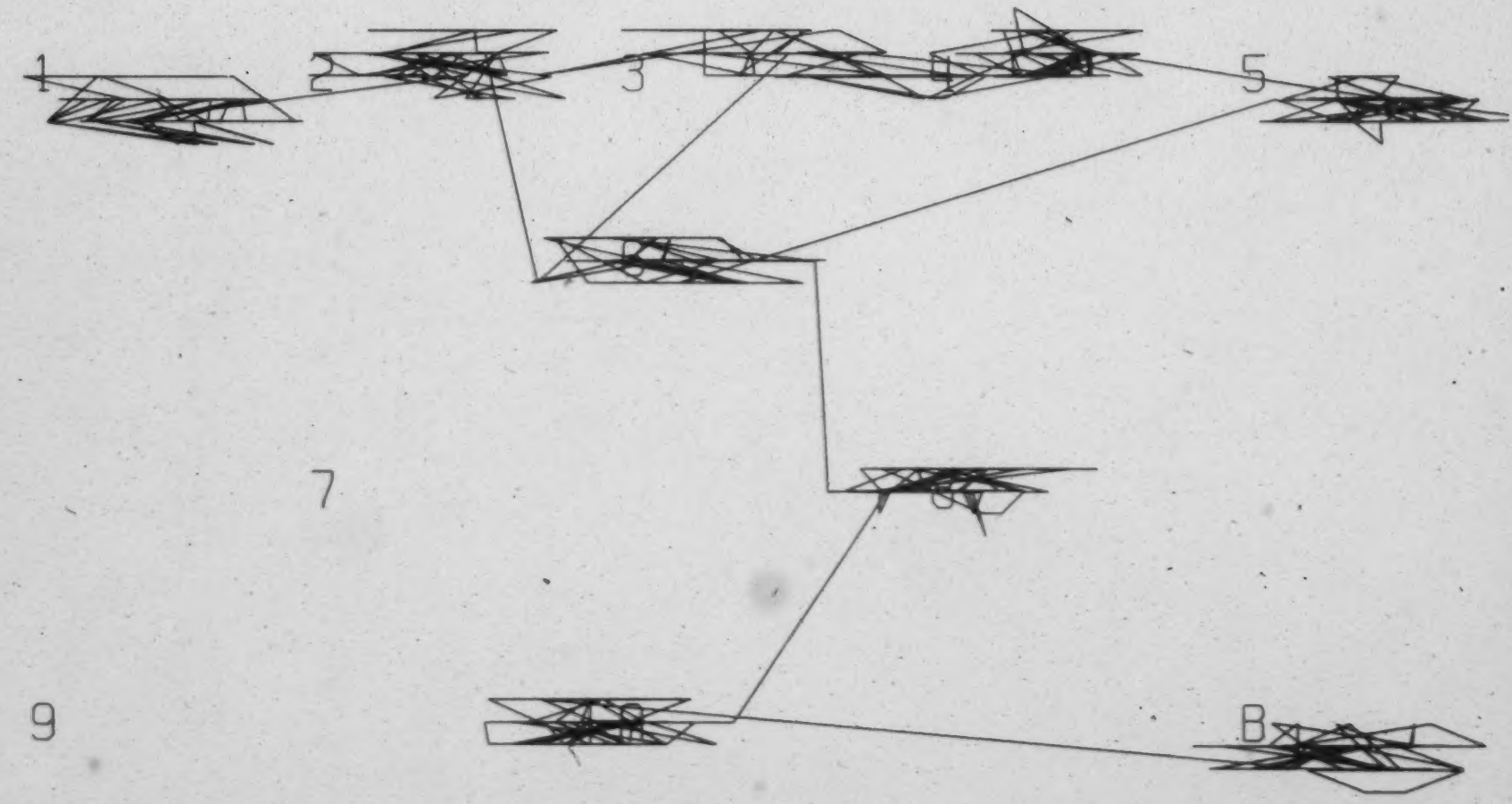


FIGURE 19

Uncorrected Eye Pointing
Positions for Subject 3
Viewing Stimulus Situation 1

fact that some regions within the video display area required angular displacements greater than 12 ½ degrees when being fixated, a procedure was developed for correcting observed eye pointing coordinates recorded when subjects fixated video display regions beyond 12 ½ degrees.

To determine which observed vertical displacements required correction, the vertical displacement ordinate that corresponded to 12 ½ degrees of displacement was calculated. Because the horizontal distance between the subject's eye and the display screen was constant at 16 inches, a vertical displacement of 12 ½ degrees was found to be (16 tan 12 ½) approximately 3 ½ inches. Since the vertical resolution for each subject was previously estimated, it was possible to calculate a critical value of vertical displacement between the corneal reflection and the pupil center, and that observed vertical displacements greater than this amount would require correction due to non-linearity. For example, the vertical resolution for subject 1 was 3.67 scan lines per inch, therefore the critical value of vertical displacement (3 ½ inches) was 3.5 x 3.68) = 12.85 scan lines.

In order to determine the vertical correction factor, it was assumed that the amount of correction necessary would be a linear function of the amount of vertical displacement greater than the critical value. The amount of non-linearity correction per scan line above the critical line was therefore computed by dividing the difference between the mean expected Y-displacement and the mean observed Y-displacement for calibration points one to five by the number of scan lines between the critical scan line and the mean observed Y-displacement for calibration points one to five. For example, the mean expected Y-

displacement for subject 1 was ((19.04 + 19.30 + 19.31 + 19.42 + 18.70) ÷ 5) = 19.15. Therefore the vertical correction factor for subject one was ((20.0 - 19.15) ÷ (19.15 - 12.85)) = 0.122 scan lines per scan line above the critical Y-displacement.

A similar procedure was implemented for determining which observed horizontal displacements required correction: except that for this case, since eye movements both to the left and to the right of the infrared light source were possible, critical values of horizontal displacement for displacements to the left and to the right of the infrared light source had to be calculated. For example, based on a horizontal resolution of 2.44 pulses per inch for subject one, the critical values of horizontal displacement for subject one (3.5 inches) were (3.5 x 2.44) = ± 8.54 pulses. The mean observed horizontal displacement between the pupil center and the center of the corneal reflection at the right edge of the screen was determined by calculating the mean observed X-displacement for calibration points five and eight. This was found to be ((1 - 8.83 + - 7.01) ÷ 2) = 7.92 for subject one. Since this was less than the critical value of horizontal displacement, no correction was necessary for subject one on observed horizontal displacements to the right. The mean observed X - displacement for calibration points one and nine was ((8.868 + 10.32) ÷ 2) = 9.50. Since this was greater than the critical value, corrections to observed X - displacement data to the left of the screen were calculated by determining a horizontal correction factor in a manner similar to that already described for calculating a vertical correction factor. For example, the horizontal correction factor for subject one to be

applied to all observed X - displacements greater than 8.54 (left of center) was (10.26 - 9.50) ÷ (9.50 - 8.54) = 0.79 pulses per pulse to the left of the critical X - displacement.

Table 8 shows a summary of X- and Y- linearity correction factors for each of the subjects tested. In order to evaluate the effect of applying these correction factors to the observed data, the observed X- and Y- displacement data for each of the calibration points was corrected.

As was noted on Tables 4 and 7 calibration data for subject three on points seven and nine was missing. The data recorded while this subject was fixating points seven and nine showed one long, continuous "blink". This occurred due to the intensity of the pupil suddenly rising to such a level that the oculometer could not distinguish between the pupil and the corneal reflection. Therefore, the horizontal displacement between points six and eight were used in order to determine the horizontal resolution. Also, the displacement for the vertical calibration axis was based on the observed displacement on point eight only rather than on the mean observed displacement for points seven and eight.

Examination of the X-displacement error scores for subject three (Table 8) and the plot of uncorrected eye pointing positions for subject three viewing the calibration points, seemed to indicate that there was a major horizontal misalignment in the calibration for subject three. Therefore, a new horizontal calibration axis was determined for subject three, based on the mean observed horizontal displacement for calibration points five and B. Table 9 shows the error table for subject

TABLE 8

X and Y Linearity Correction Factors

Subject	Critical Y-Disp.	Critical X-Disp.	Mean Y-Disp. Pts.1-5	Mean X-Disp. Pts. 5,B	Mean X-Disp. Pts.1,9	X-Corr. Factor	Y-Corr. Factor
1	12.88	±8.54	19.15	-7.92	9.50	.792	.122
2	13.68	±9.87	21.88	-1.32	20.67	.0056	.098
3	11.72	±7.07	18.43	-9.00	6.73		.037

TABLE 9

Error Table for Subject 3 Based on Corrected Horizontal Calibration Axis

Calib. Point	Expected X-Disp.	Observed X-Disp.	X Error	Expected Y-Disp.	Observed Y-Disp.	Y Error
1	6.76	6.73	.03	18.68	17.72	.96
2	3.12	3.05	.07	18.68	18.70	.02
3	- .92	1.58	.64*	18.68	18.95	.27
4	-4.96	-4.93	.03	18.68	18.93	.25
5	-9.00	-9.24	.24	18.68	17.84	.84
6	- .92	.46	1.38*	14.66	14.52	.14
7	3.12	**		9.56	**	**
8	-4.96	-3.52	1.44*	9.56	9.63	.07
9	6.76	**	**	4.61	**	**
A	- .92	1.01	.09	4.61	4.47	.14
B	-9.00	-8.76	.24	4.61	3.89	.72

*Denotes errors greater than one character in size.

**Denotes missing data.

three based on the corrected horizontal calibration axis. The number of calibration points falling more than one character width away from the mean observed X-displacement was reduced from seven to three as a result of this correction.

The corrected eye movement data for each subject viewing stimulus situation one was again plotted and is presented in Figures 20-22.

Stimulus Situations Two to Four

As described earlier, stimulus situation two appeared on the display screen immediately after the last calibration point. It consisted of eight lines of text as shown in Figure 14. The word "large" was deliberately spelled "laarge" in line six of this stimulus situation.

This stimulus situation appeared on the screen for twenty seconds. All subjects completed reading the material in less than the twenty seconds to finish reading. Since the number chosen to designate a blink was purely arbitrary and of no numerical significance in analysis, all blinks were removed from the recorded data prior to further analysis, although data regarding when blinks occurred and their duration was available. The appropriate corrections for non-linearity were made to the data. Finally, in order to more clearly distinguish between subjects' eye movements while reading and subjects' eye movements while waiting for the next stimulus situation, the data was separated into two parts. In all cases, visual inspection of the displacement coordinates clearly revealed when the subject had reached the lower right corner of the

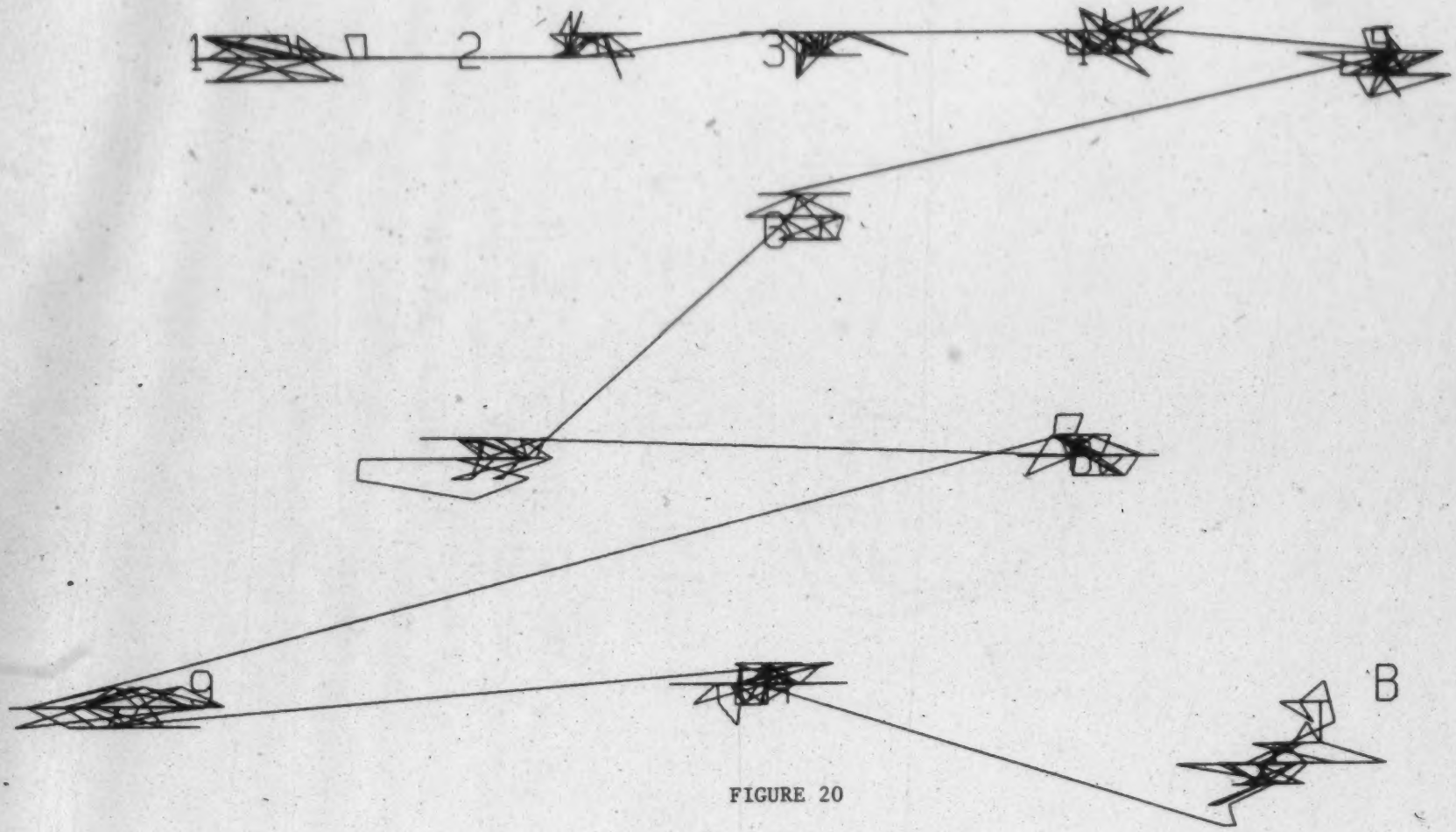


FIGURE 20

Corrected Eye Pointing
Positions for Subject 1
Viewing Stimulus Situation 1

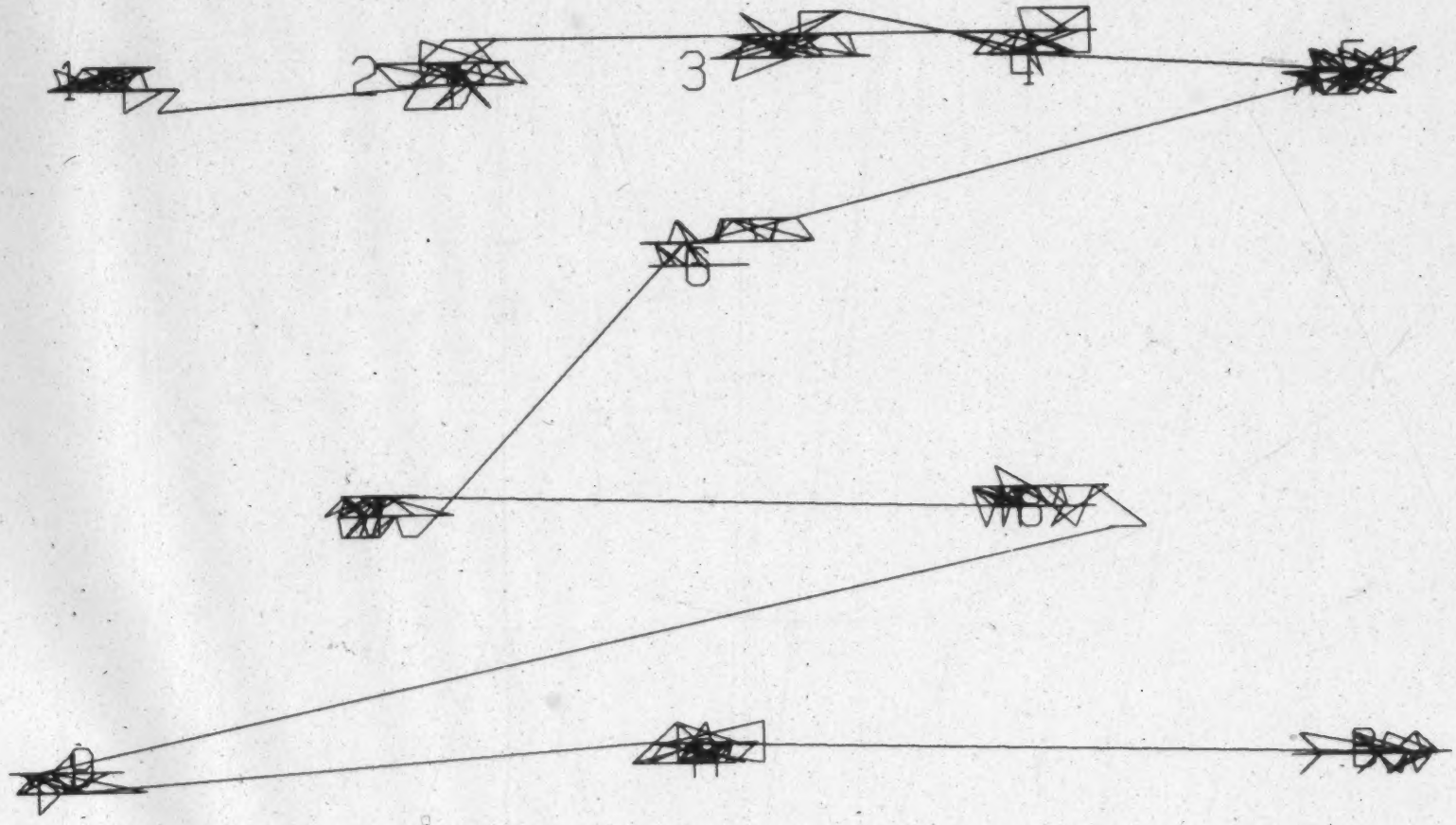


FIGURE 21

Corrected Eye Pointing
Positions for Subject 2
Viewing Stimulus Situation 1

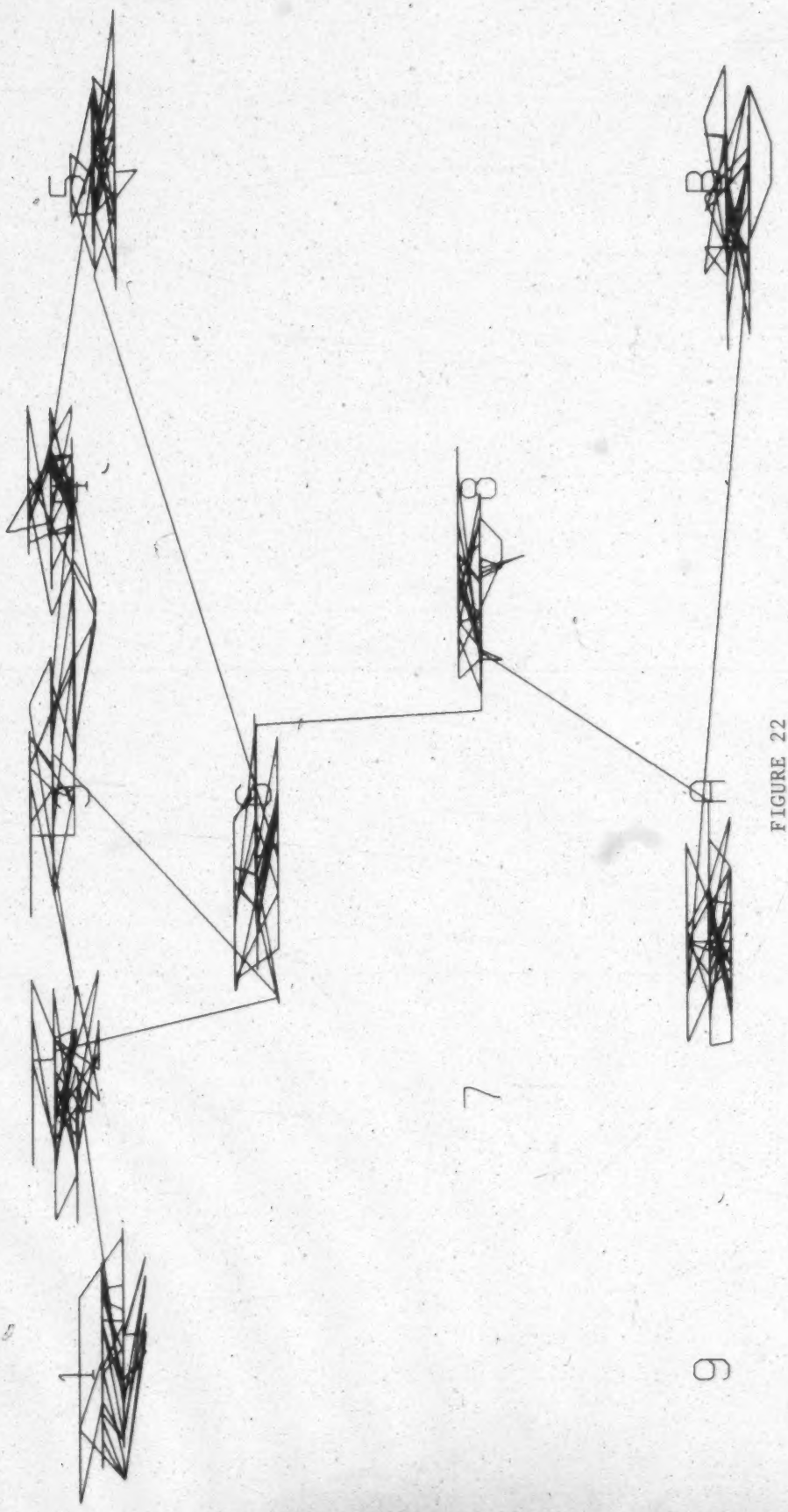


FIGURE 22

Corrected Eye Pointing
Positions for Subject 3
Viewing Stimulus Situation 1

display screen for the first time, signifying completion of reading.

Figures 23,25 and 27 show plots of subjects' eye movements while reading the text presented in stimulus situation one while Figures 24 and 26 show plots of subjects' eye movements after finishing reading the text. Because of the complexity of stimulus situation 4, it was not possible to determine the point at which a subject had finished viewing this stimulus situation, therefore separate plots of eye movements after finishing reading stimulus situation 4 were not made. Readings for stimulus situation 2 and 3 were corrected for non-linearity after removing blinks in exactly the same manner as described above. Plots of eye movements for these stimulus situations are shown in Figures 27 to 37.

Examination of Figures 23, 24, 28, 29, and 33 revealed what appeared to be an increased amount of fixation by all three subjects on the mis-spelled word "large". This correspondence between this increased amount of fixation and the word would certainly suggest that overall calibration of the system had been achieved. However, examination of Figures 28 to 32, the plots of corrected eye movements for subject two seemed to reveal that the vertical registration near the top of the screen was not satisfactory. As a result, the data for subject two was replotted, using only a horizontal correction factor. Figures 38 to 42 show these plots. It appeared that better vertical registration was achieved for subject two without vertical correction of the data.

As has already been mentioned, data regarding the occurrence and duration of blinks was available. Data regarding pupil dilation was also available. Figure 43 shows changes in dilation observed for

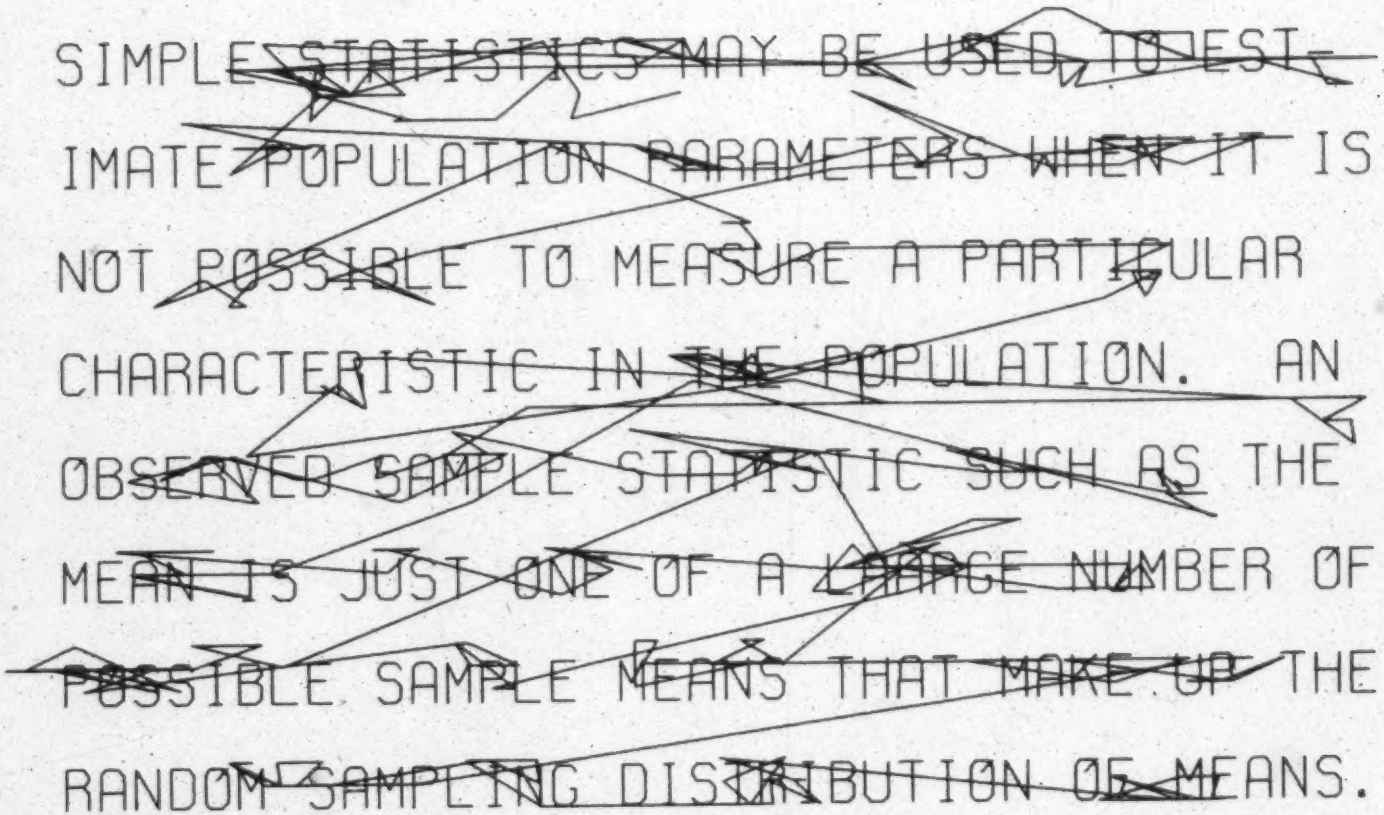

SIMPLE STATISTICS MAY BE USED TO ESTI-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 23

Corrected Eye Movements
for Subject 1 Reading
Stimulus Situation 2

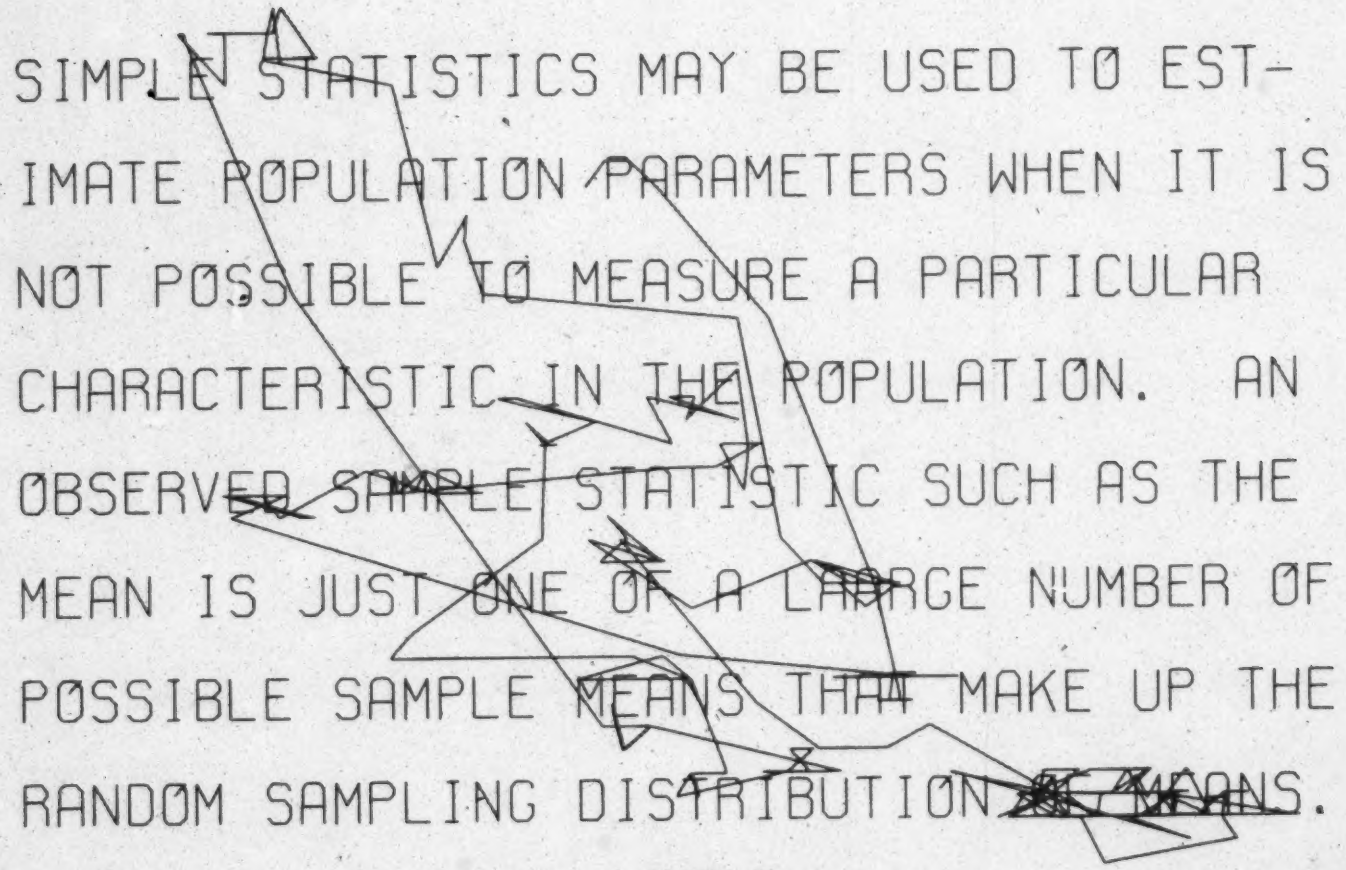

SIMPLE STATISTICS MAY BE USED TO EST-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 24

Corrected Eye Movements
For Subject 1 Waiting For
Stimulus Situation 3

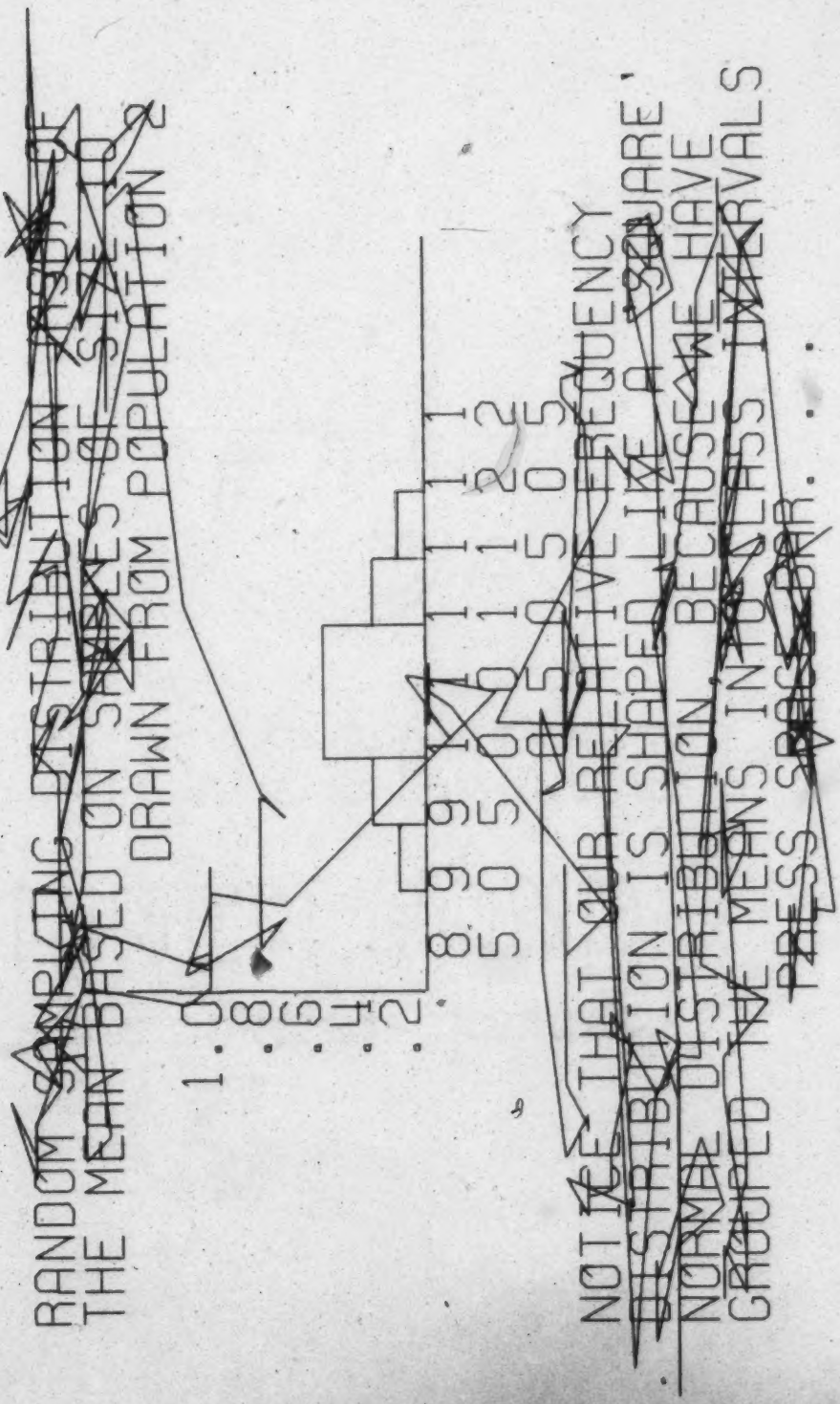

RANDOM SAMPLING DISTRIBUTION OF
THE MEAN BASED ON SAMPLES OF SIZE 2
DRAWN FROM POPULATION
1.0
.8
.6
.4
.2
8 9 9 4 1 1 1 1 1
5 0 5 0 5 0 1 1 2 2
NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR. . .

FIGURE 25

Corrected Eye Movements
for Subject 1 reading
Stimulus Situation 3

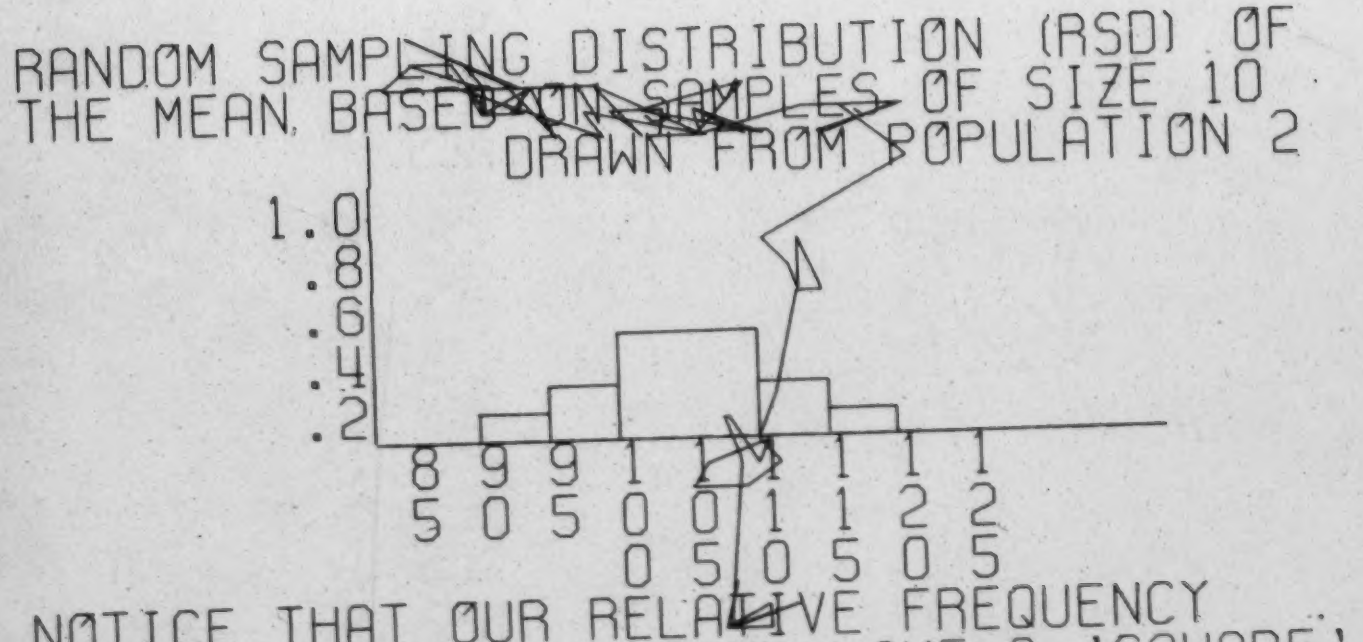

RANDOM SAMPLING DISTRIBUTION (RSD) OF
THE MEAN BASED ON SAMPLES OF SIZE 10
DRAWN FROM POPULATION 2
1.0
.8
.6
.4
.2
8 9 9 1 1 1 1 1
5 0 5 0 0 1 1 2 2
0 5 0 5 0 5
NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR. . .

FIGURE 26

Corrected Eye Movements
For Subject 1 Waiting For
Stimulus Situation 4

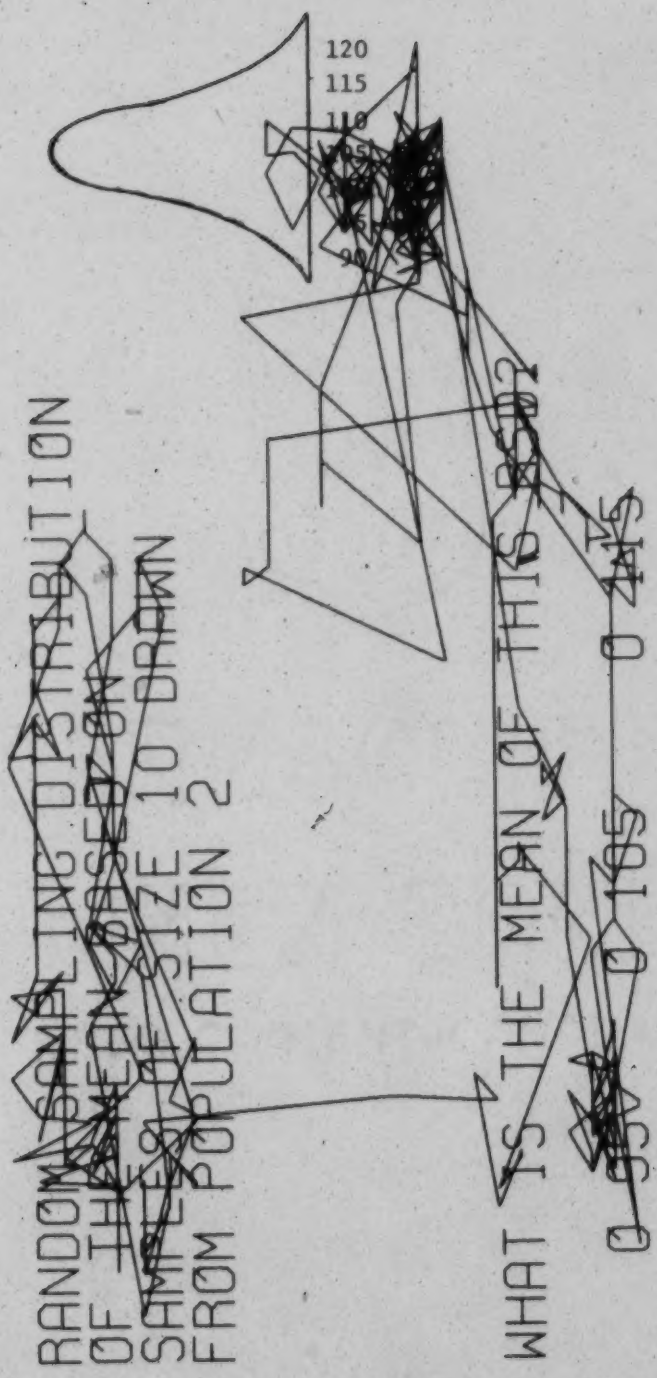


FIGURE 27

Corrected Eye Movements
for Subject 1 Reading
Stimulus Situation 4

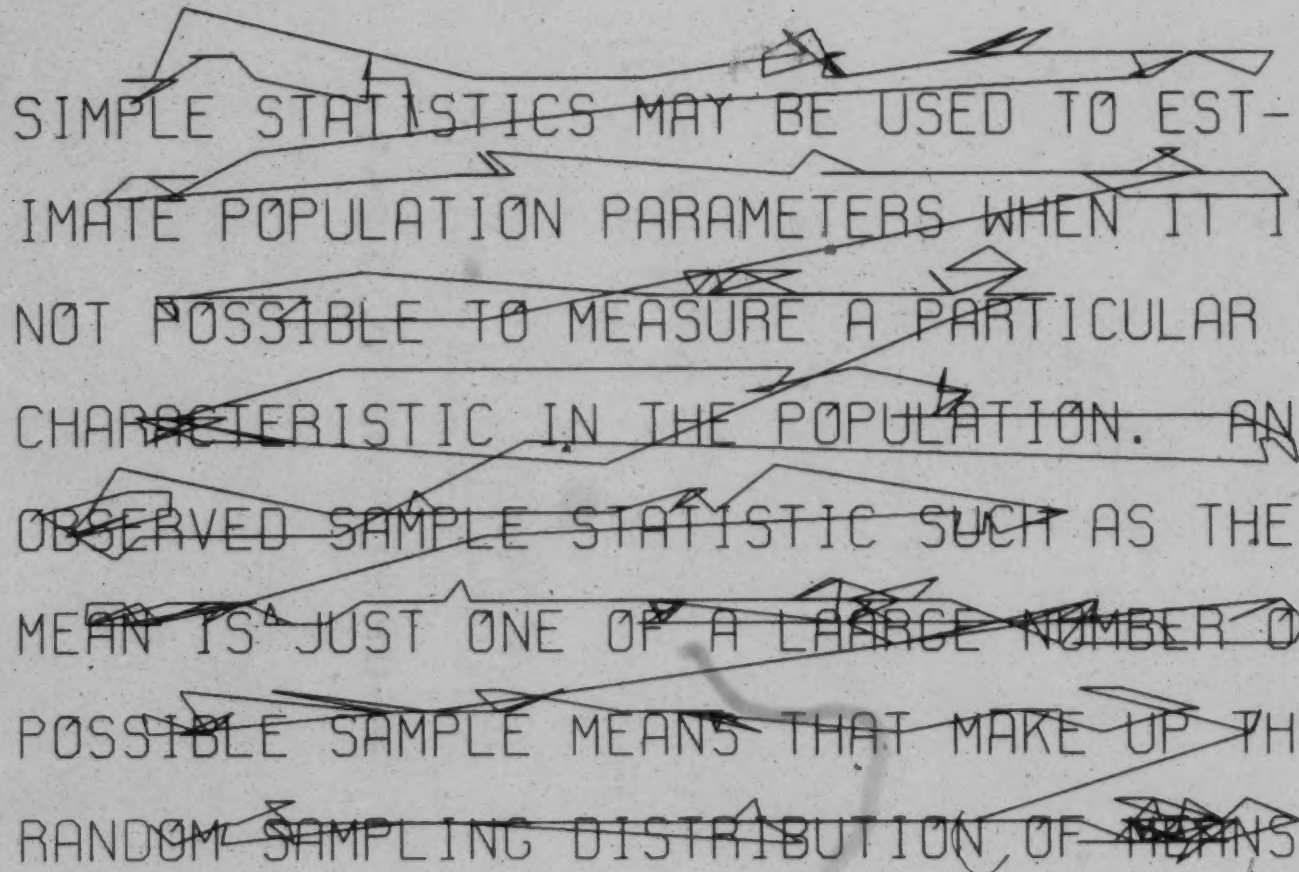

SIMPLE STATISTICS MAY BE USED TO EST-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 28

Corrected Eye Movements
for Subject 2 Reading
Stimulus Situation 2

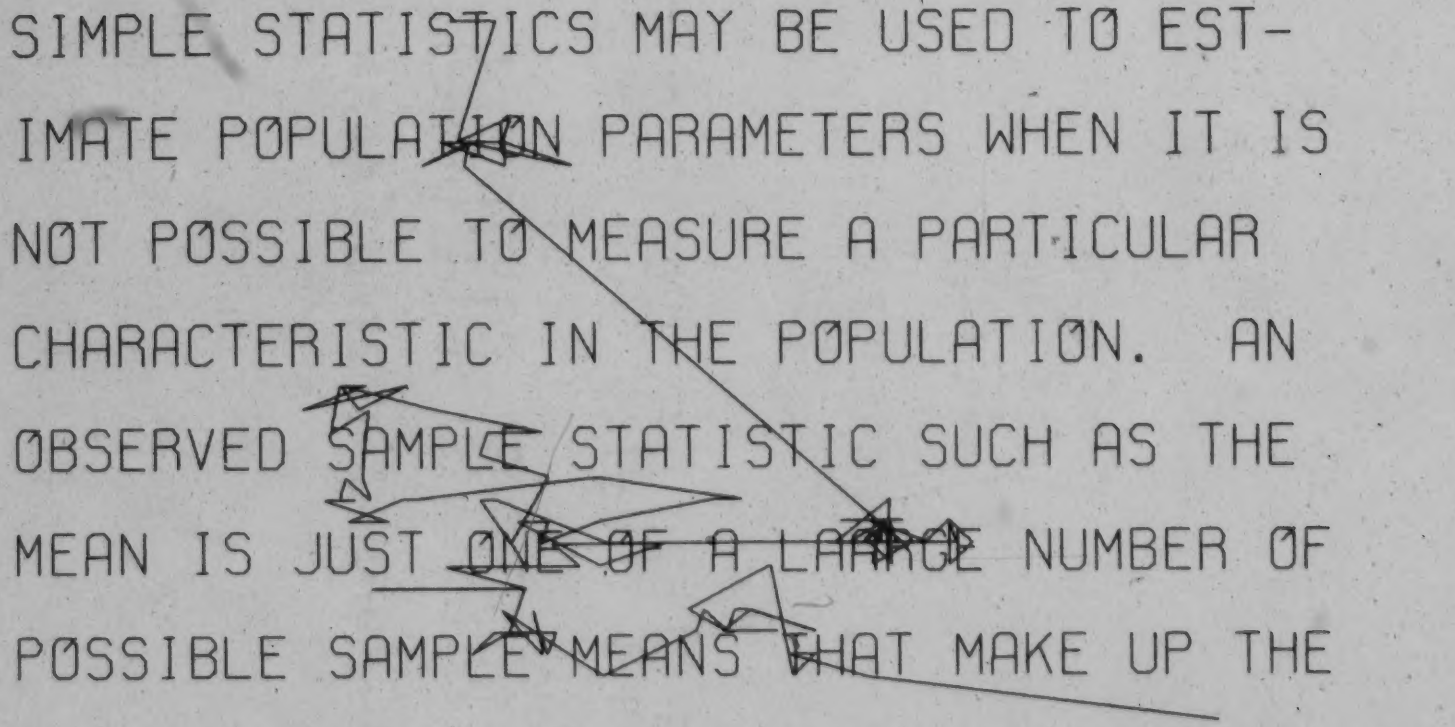

SIMPLE STATISTICS MAY BE USED TO EST-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 29

Corrected Eye Movements
for Subject 2 Waiting for
Stimulus Situation 3

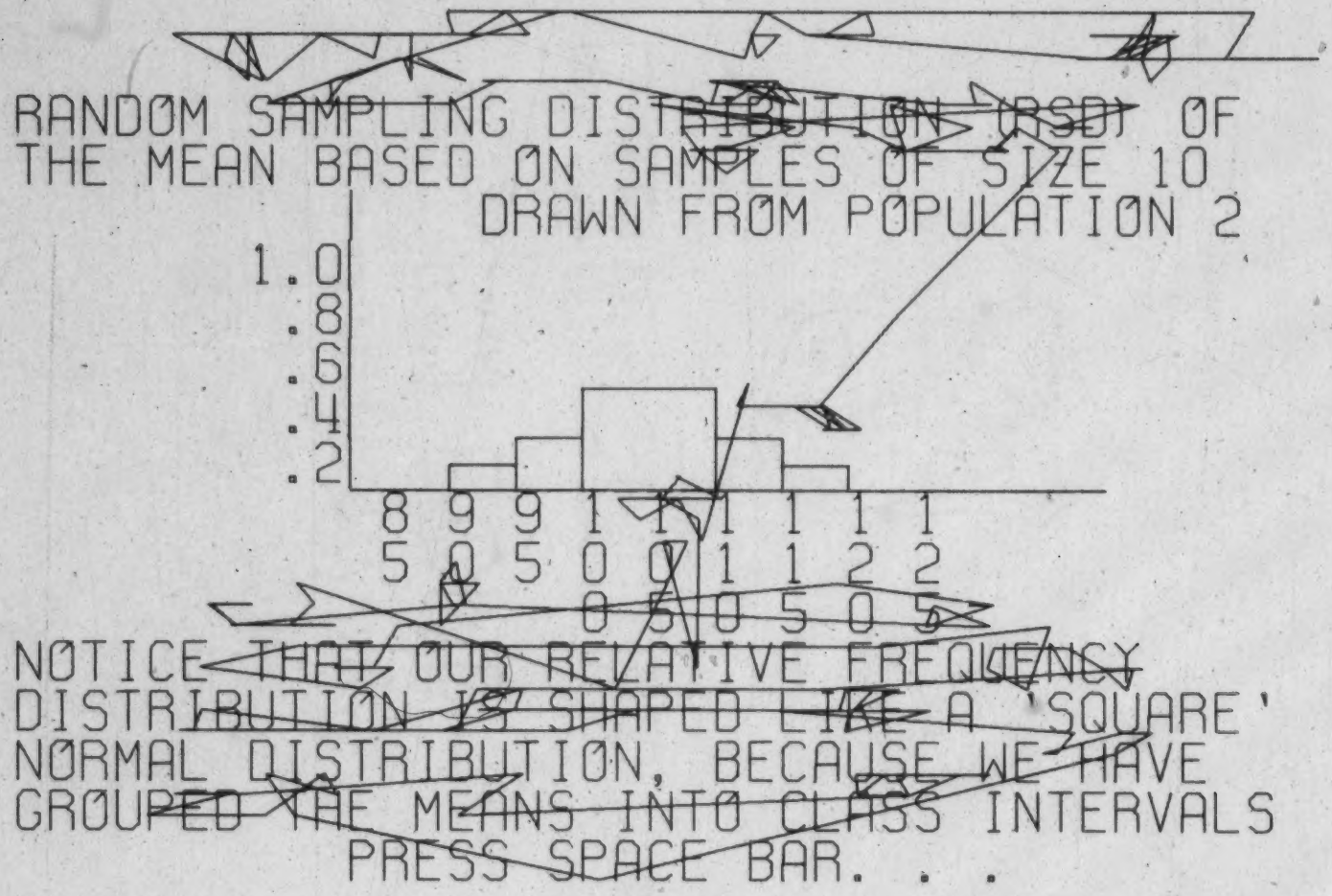

RANDOM SAMPLING DISTRIBUTION (RSD) OF
THE MEAN BASED ON SAMPLES OF SIZE 10
DRAWN FROM POPULATION 2
1.0
.8
.6
.4
.2
8 9 9 1 1 1 1 1 1 1
5 0 5 0 0 1 1 2 2
0 5 0 5 0 5
NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR. . .

FIGURE 30

Corrected Eye Movements
for Subject 2 Reading
Stimulus Situation 3

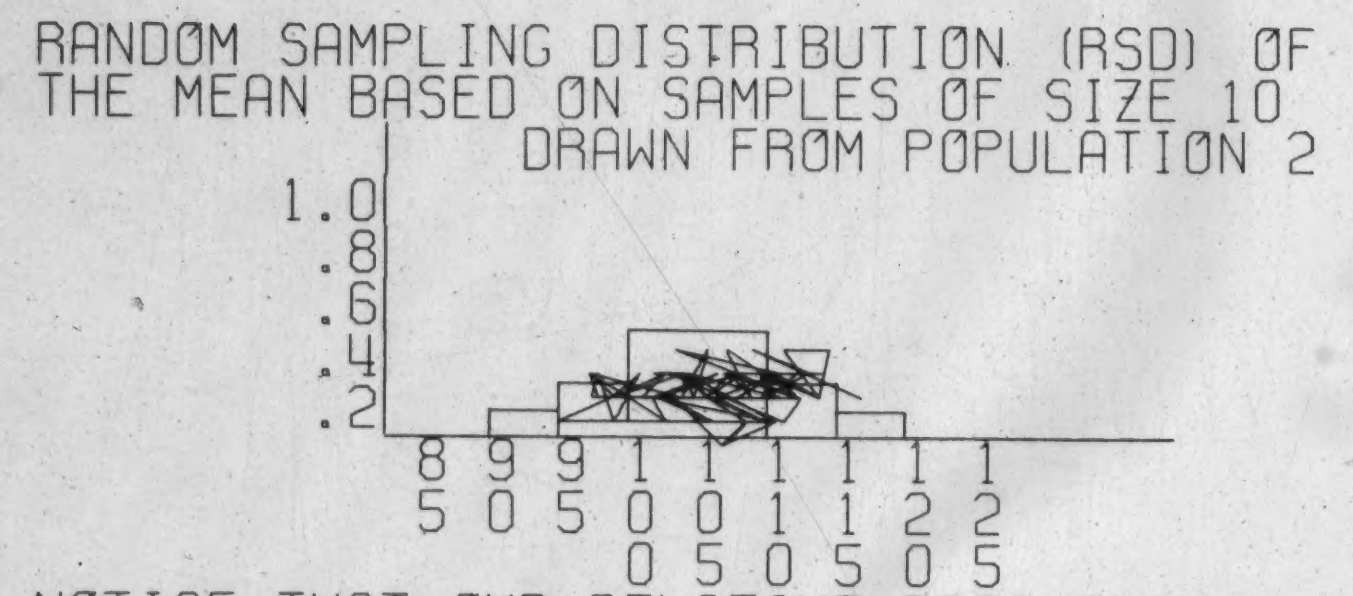

RANDOM SAMPLING DISTRIBUTION (RSD) OF
THE MEAN BASED ON SAMPLES OF SIZE 10
DRAWN FROM POPULATION 2
1.0
.8
.6
.4
.2
8 9 9 1 1 1 1 1 1
5 0 5 0 0 1 1 2 2
0 5 0 5 0 5
NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR. . .

FIGURE 31

Corrected Eye Movements
for Subject 2 Waiting for
Stimulus Situation 4

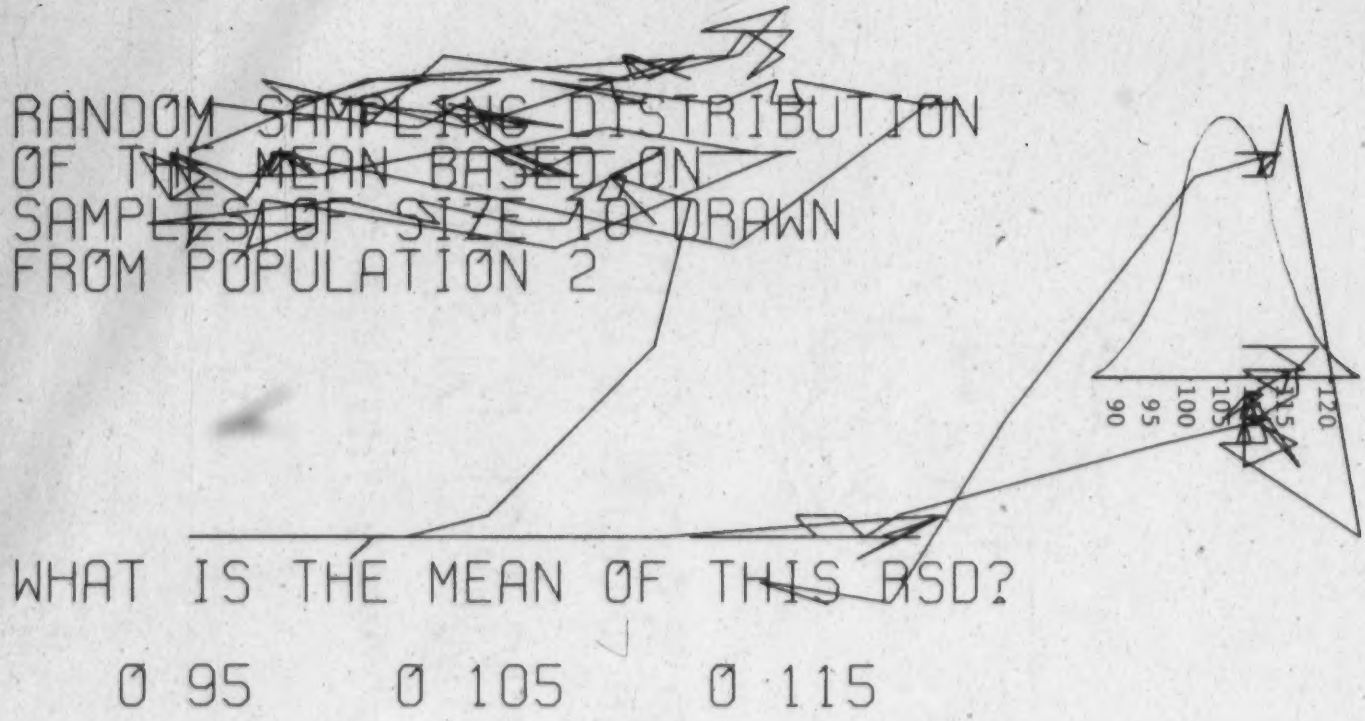


FIGURE 32

Corrected Eye Movements
for Subject 2 Reading
Stimulus Situation 4

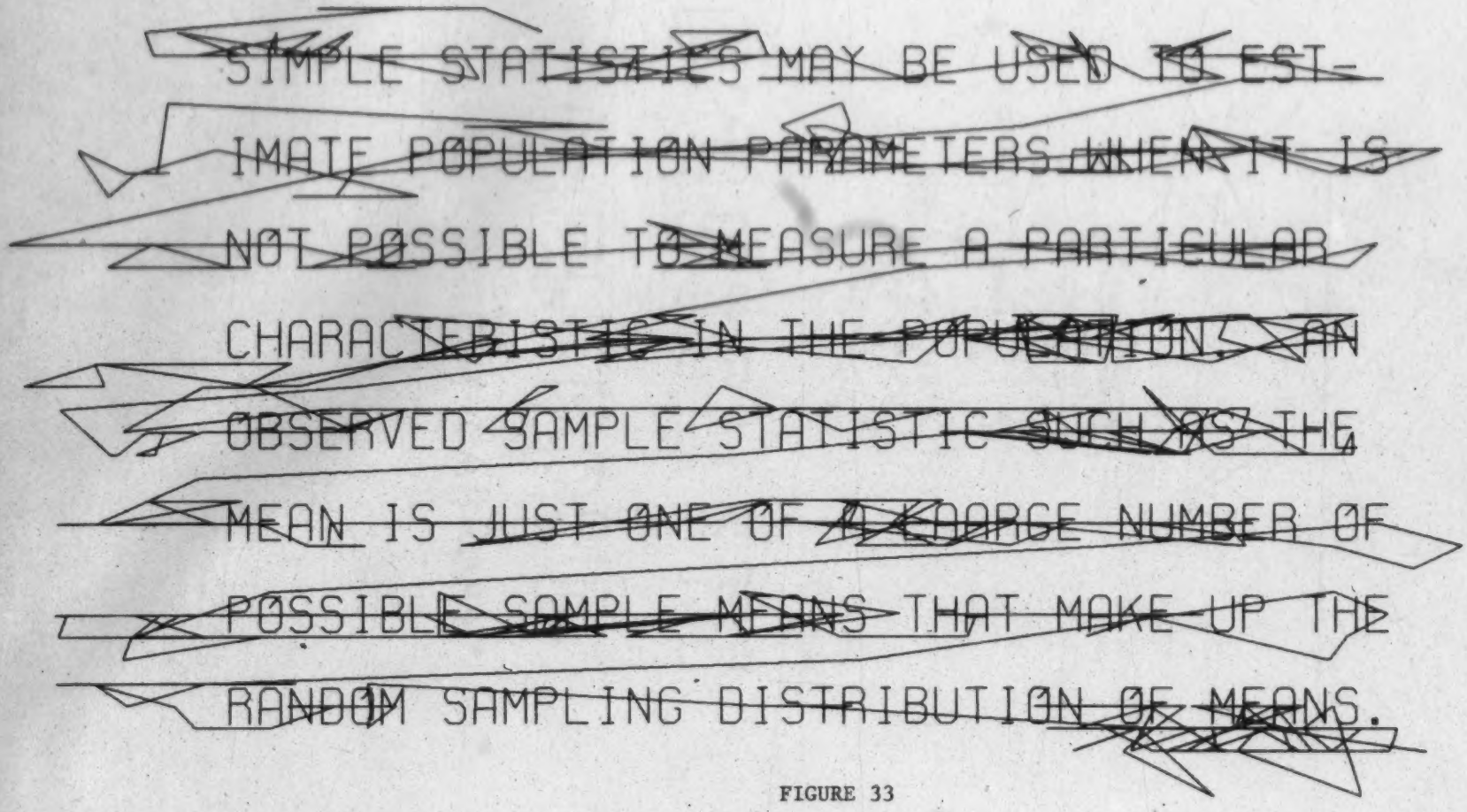

SIMPLE STATISTICS MAY BE USED TO ESTI-
MATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 33

Corrected Eye Movements
for Subject 3 Reading
Stimulus Situation 2

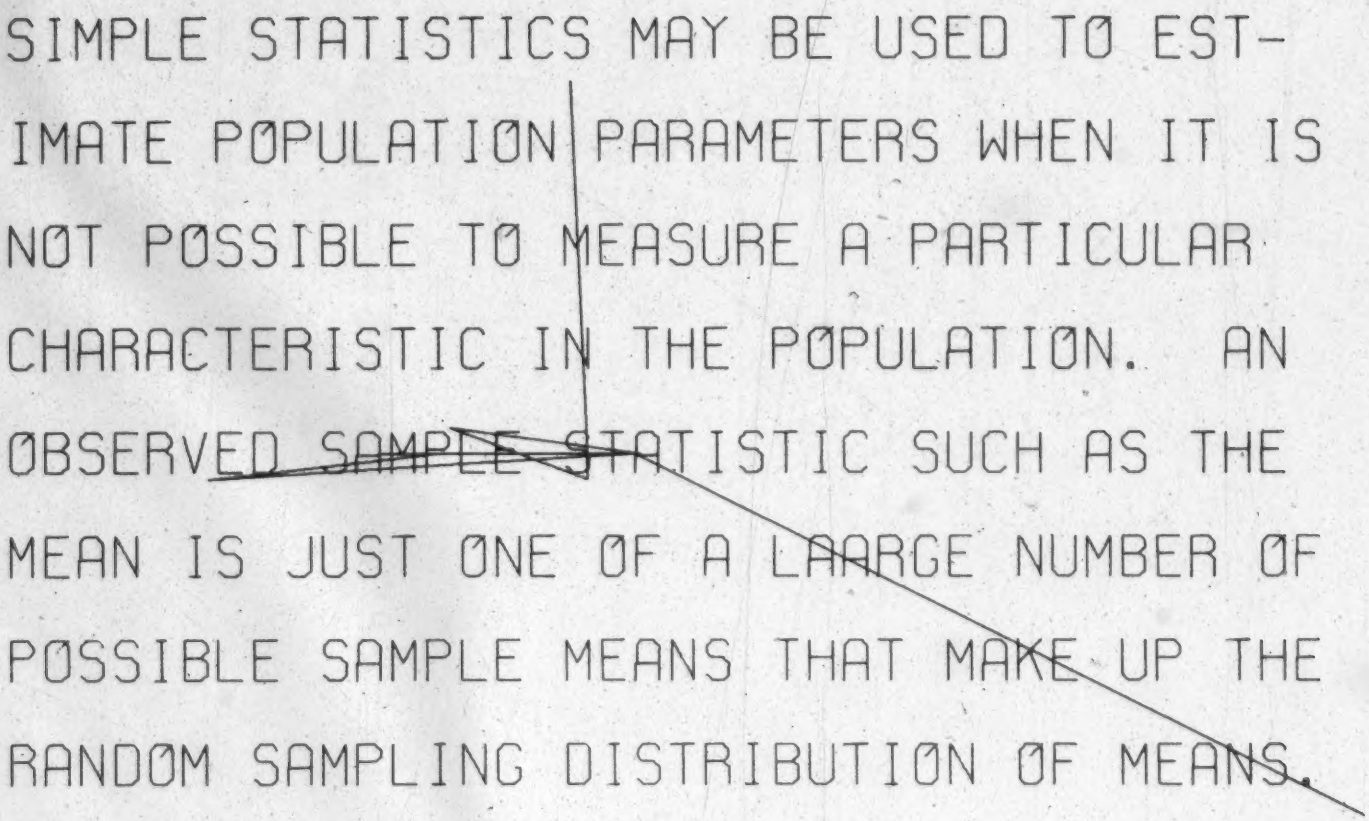

SIMPLE STATISTICS MAY BE USED TO EST-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 34

Corrected Eye Movements
for Subject 3 Waiting for
Stimulus Situation 3

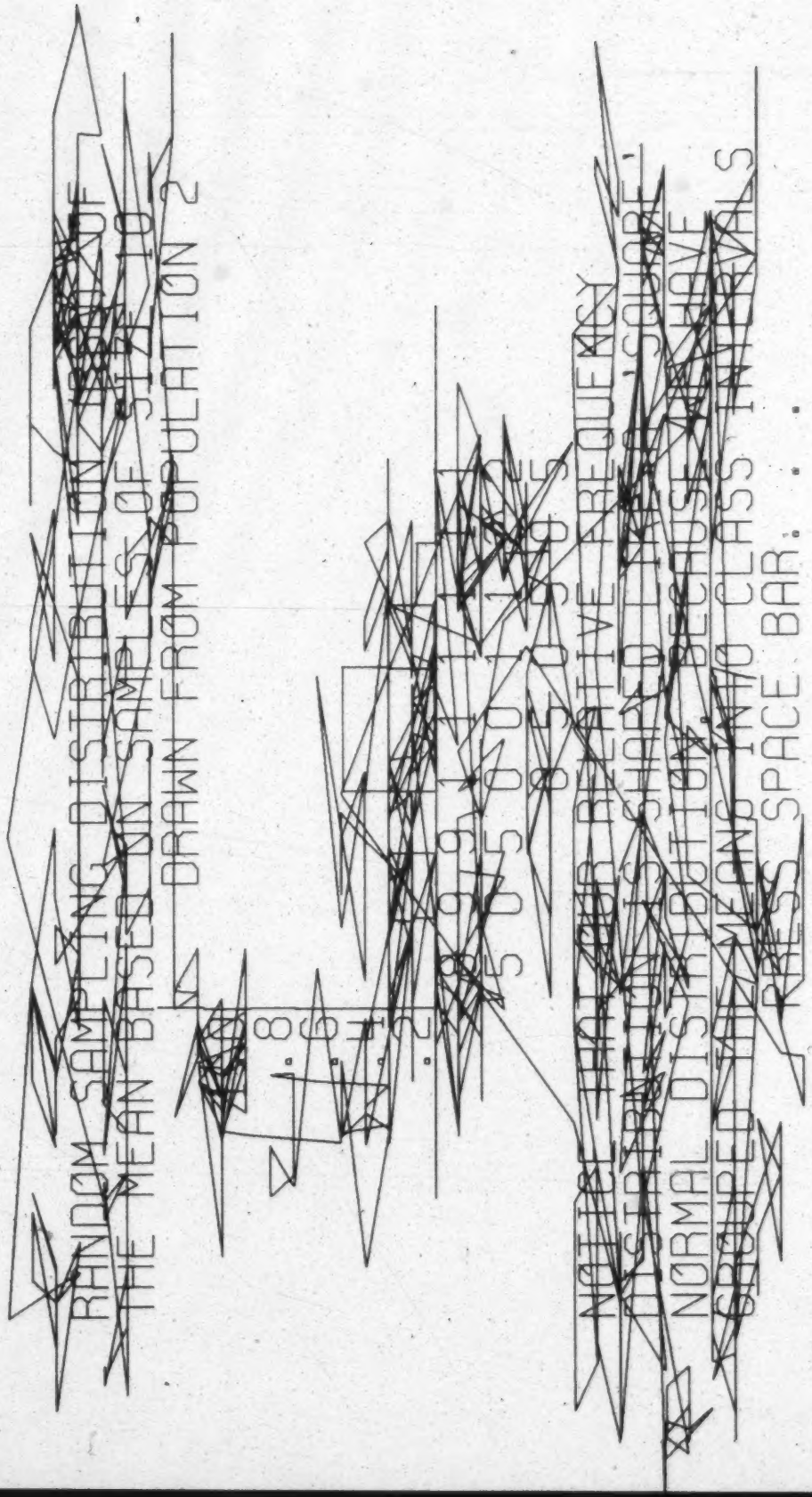


FIGURE 35

Corrected Eye Movements
for Subject 3 Reading
Stimulus Situation 3

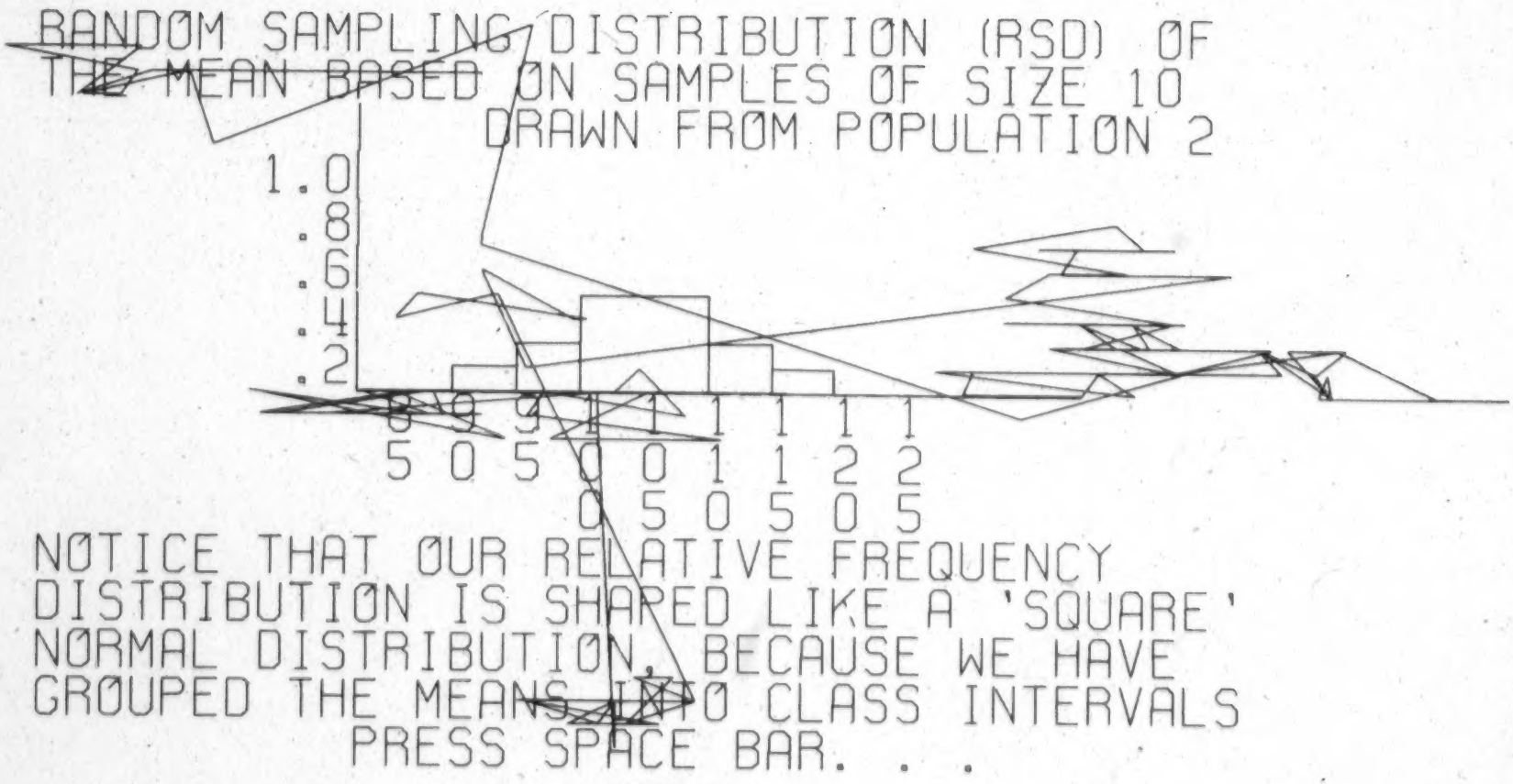


FIGURE 36

Corrected Eye Movements
for Subject 3 Waiting for
Stimulus Situation 4

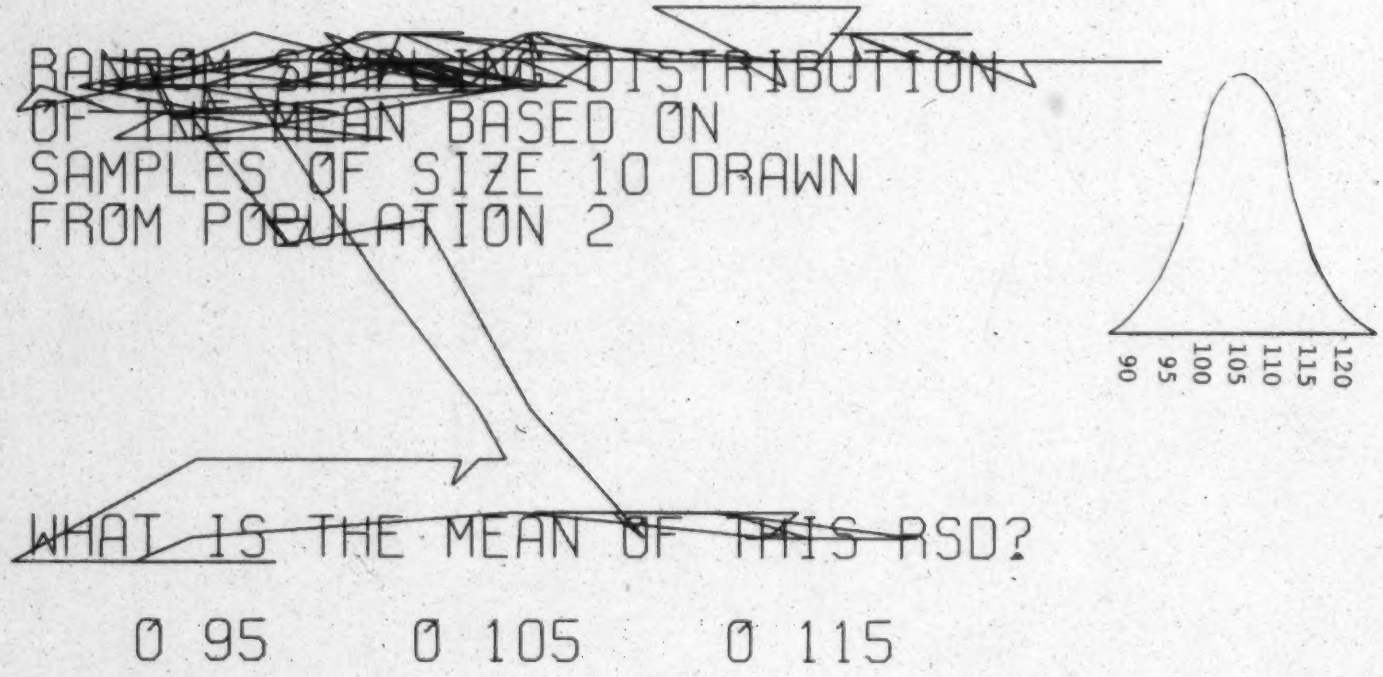


FIGURE 37

Corrected Eye Movements
for Subject 3 Reading
Stimulus Situation 4

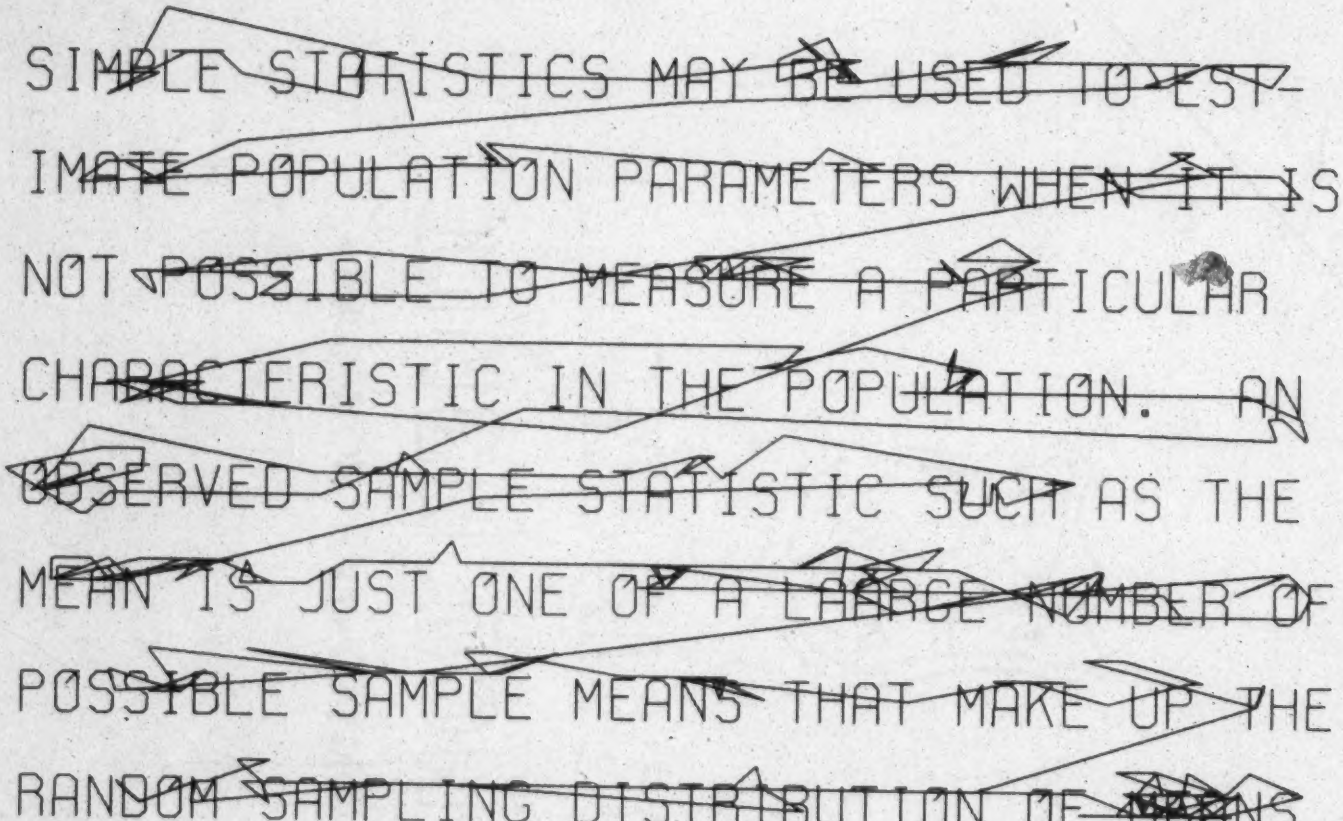

SIMPLE STATISTICS MAY BE USED TO ESTIMATE POPULATION PARAMETERS WHEN IT IS NOT POSSIBLE TO MEASURE A PARTICULAR CHARACTERISTIC IN THE POPULATION. AN OBSERVED SAMPLE STATISTIC SUCH AS THE MEAN IS JUST ONE OF A LARGE NUMBER OF POSSIBLE SAMPLE MEANS THAT MAKE UP THE RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 38

Uncorrected Eye Movements
for Subject 2 Reading
Stimulus Situation 2

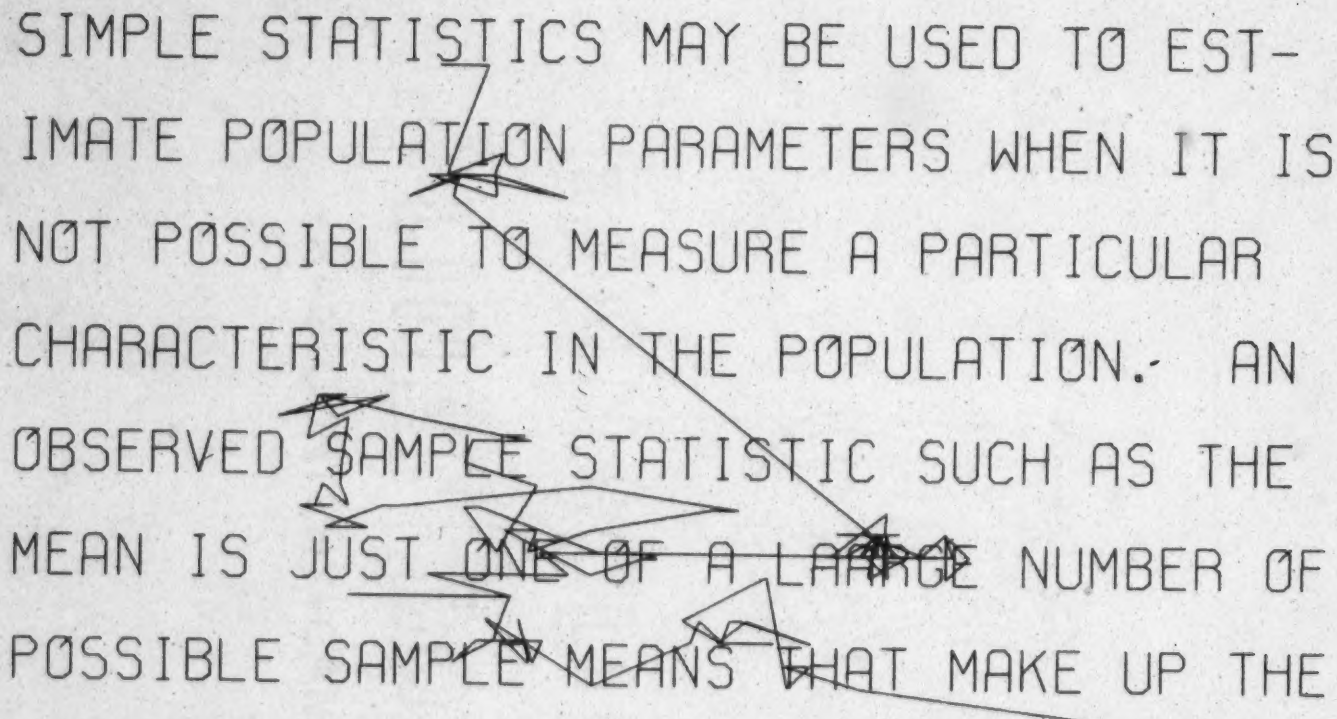

SIMPLE STATISTICS MAY BE USED TO EST-
IMATE POPULATION PARAMETERS WHEN IT IS
NOT POSSIBLE TO MEASURE A PARTICULAR
CHARACTERISTIC IN THE POPULATION. AN
OBSERVED SAMPLE STATISTIC SUCH AS THE
MEAN IS JUST ONE OF A LARGE NUMBER OF
POSSIBLE SAMPLE MEANS THAT MAKE UP THE
RANDOM SAMPLING DISTRIBUTION OF MEANS.

FIGURE 39

Uncorrected Eye Movements
for Subject 2 Waiting for
Stimulus Situation 3

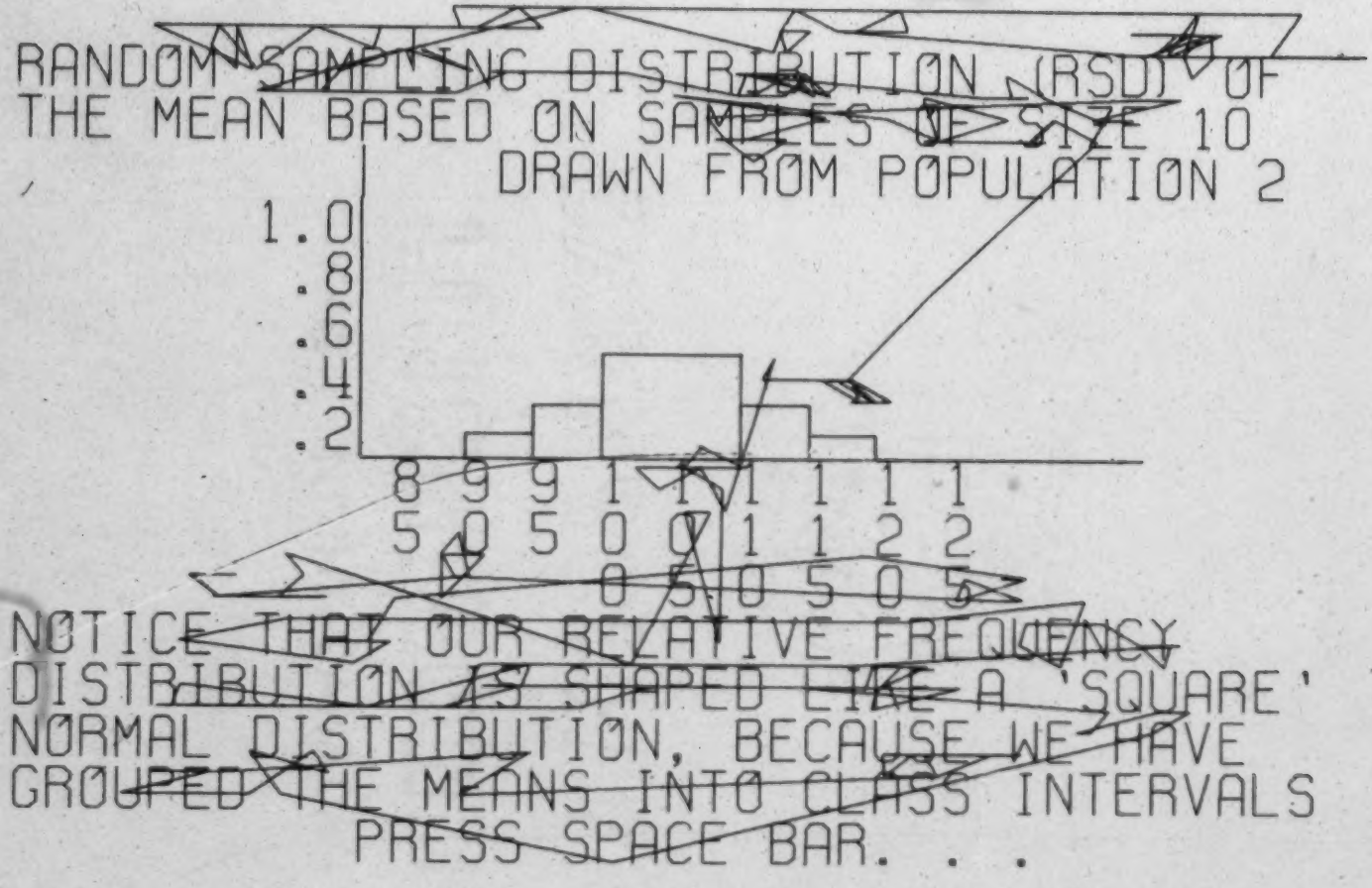

RANDOM SAMPLING DISTRIBUTION (RSD) OF
THE MEAN BASED ON SAMPLES OF SIZE 10
DRAWN FROM POPULATION 2
1.0
.8
.6
.4
.2
8 9 9 1 1 1 1 1 1
5 0 5 0 0 1 1 2 2
0 5 0 5 0 5
NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR. . .

FIGURE 40

Uncorrected Eye Movements
for Subject 2 Reading
Stimulus Situation 3

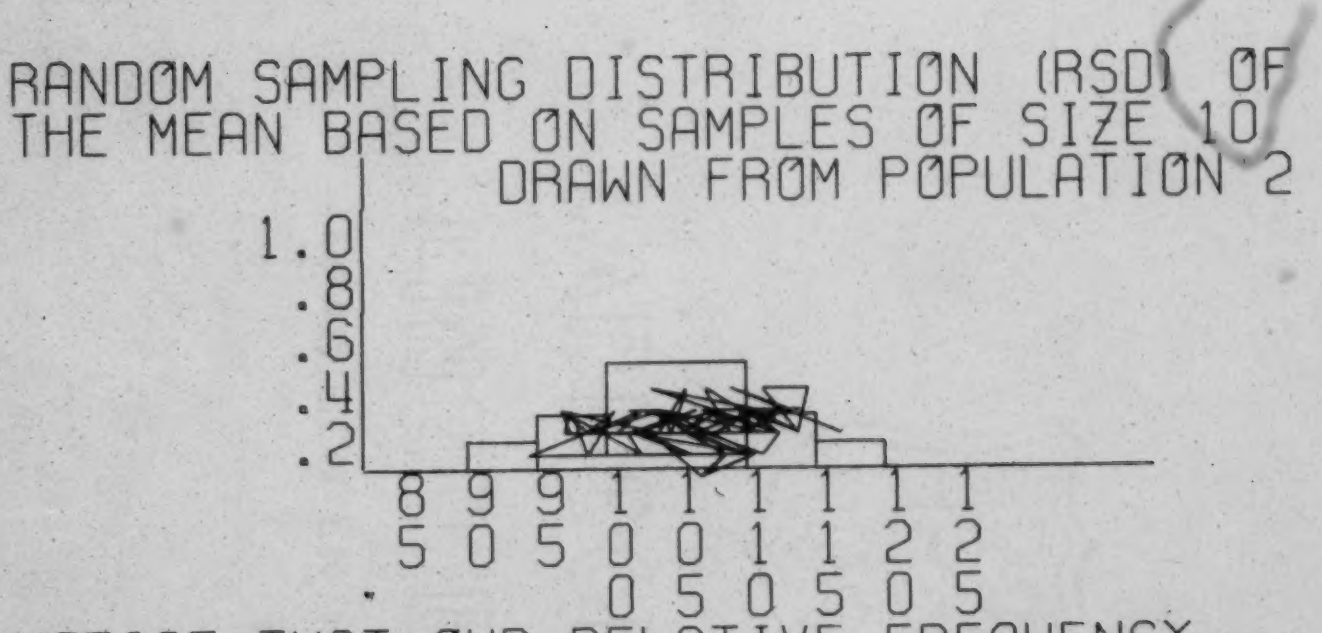

RANDOM SAMPLING DISTRIBUTION (RSD) OF
THE MEAN BASED ON SAMPLES OF SIZE 10
DRAWN FROM POPULATION 2
1.0
.8
.6
.4
.2
8 9 9 1 1 1 1 1 1
5 0 5 0 0 0 1 1 2 2
0 5 0 5 0 5
NOTICE THAT OUR RELATIVE FREQUENCY
DISTRIBUTION IS SHAPED LIKE A 'SQUARE'
NORMAL DISTRIBUTION, BECAUSE WE HAVE
GROUPED THE MEANS INTO CLASS INTERVALS
PRESS SPACE BAR. . .

FIGURE 41

Uncorrected Eye Movements
for Subject 2 Waiting for
Stimulus Situation 4

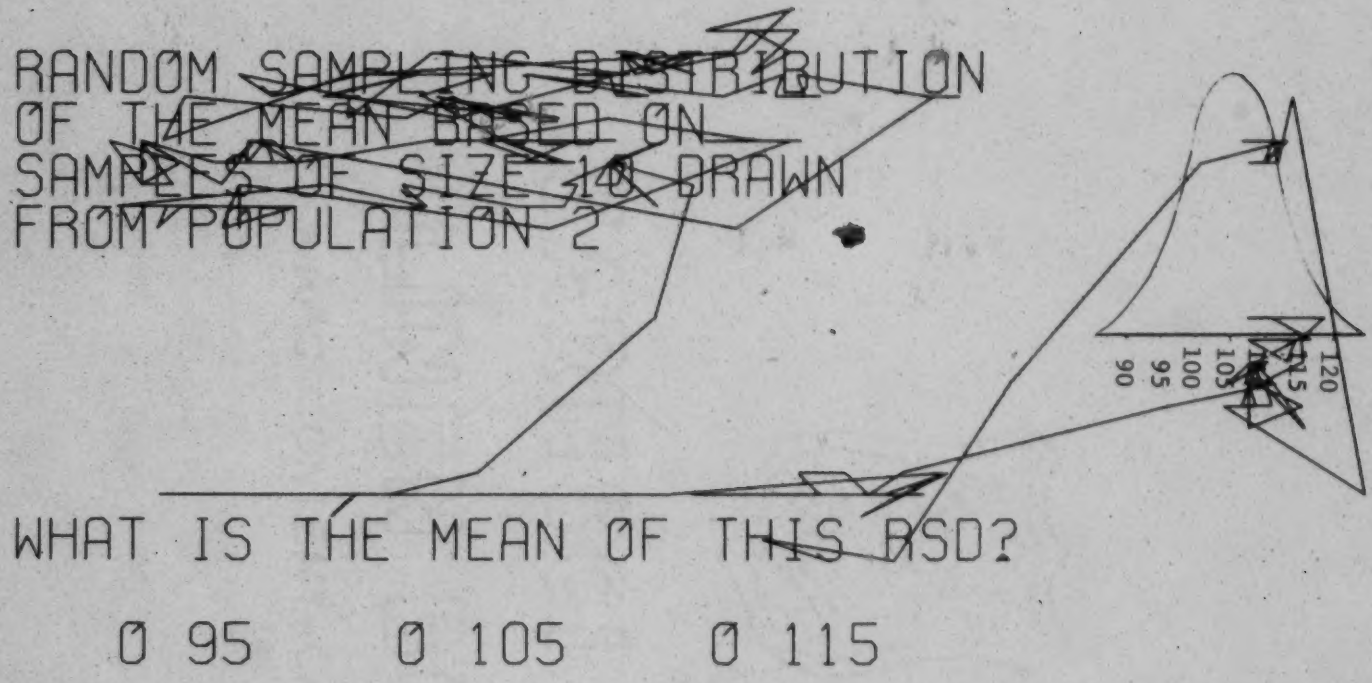


FIGURE 42

Uncorrected Eye Movements
for Subject 2 Reading
Stimulus Situation 4

1 of

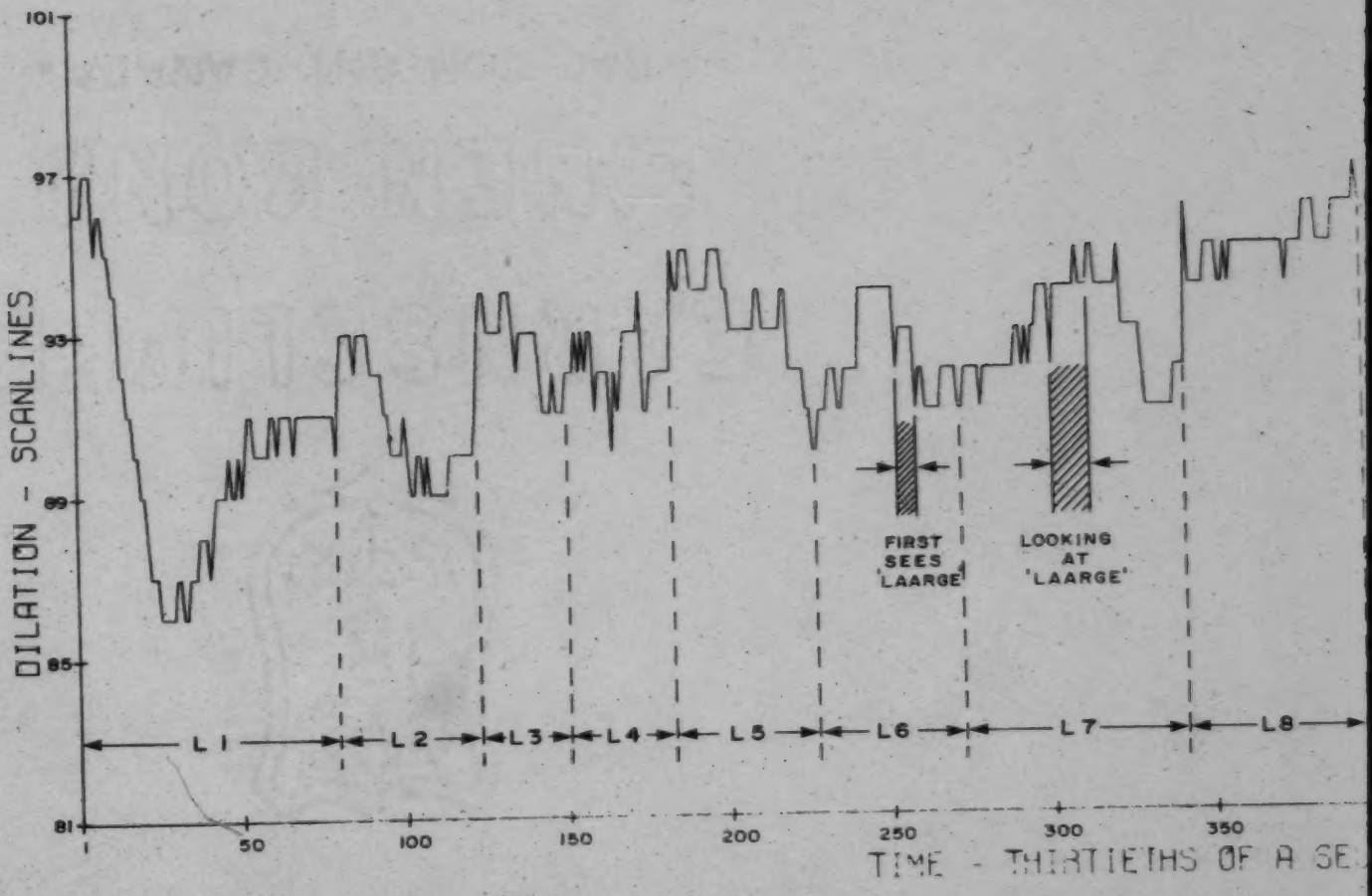


FIGURE 43

Pupil Dilations for Subje
Reading Stimulus Situati

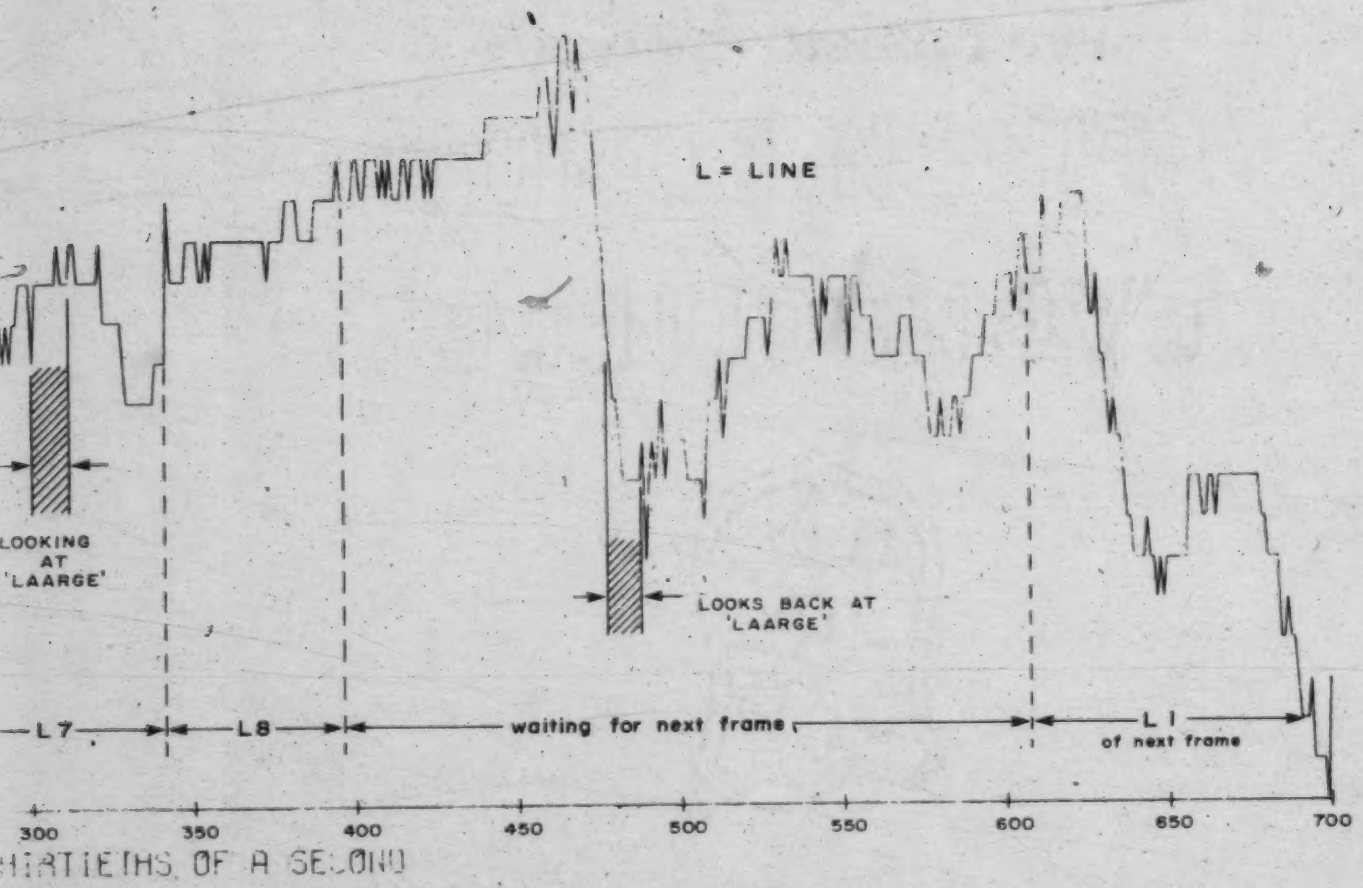


FIGURE 43

Pupil Dilations for Subject 1
Reading Stimulus Situation 2

subject one while viewing stimulus situation two. The dilations for the remaining subjects have not been plotted.

It was noted that approximately eight consecutive seconds of eye movements for subject two were lost while the subject was viewing frame three because of a sudden increase in pupil intensity to a point where the pupil signal level was sufficient to activate the corneal reflection circuits. This was recorded as an eight second blink.

Stimulus Situation Five - Calibration Check

In order to confirm the calibration of the system, the calibration display used in stimulus situation one was presented to subjects at the end of stimulus situation four. The data obtained in this manner proved to be of little value as subjects verbally confirmed that they tended to look at the position on the video display where they expected the next calibration point to appear. This data was therefore not reported in this study.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

Because so much of what a learner learns is presented to him via the visual channel, it is important to educators, particularly those who wish to study learning and attention, to be able to monitor the visual response of the learner. During this century, a number of different methods for monitoring visual response have been used with varying degrees of success. This study described and documented the development of a computer based system for recording eye movements derived from observation of the position of the corneal reflection relative to the pupil center, using an infrared television camera interfaced to a small digital computer.

The infrared computer based oculometer described in this study was developed in order to provide a means of studying eye movements of learners in relation to learning and attention. In Chapter III, six requirements for an effective oculometer system were specified. These were that:

1. The measuring and recording apparatus be relatively unobtrusive.
2. The equipment require no mechanical attachment to the subject.
3. The equipment place as few unnatural constraints (such as restriction of head movement) on the subject as possible.
4. As many oculographic characteristics as possible be recorded simultaneously.
5. The data be in a form that is readily accessible for analysis by computer.

6. The equipment be sensitive enough to detect, and fast enough to record all types of conjugate eye movements.

The infrared computer based oculometer system described in this study is relatively unobtrusive, in that the only part of the system that need be seen by the subject is the faint red glow of the illuminating source of light. The computer and its peripheral devices can be physically located in a separate room. In the event that the red light produced by the system is considered too obtrusive in a given situation, then the addition of a simple inexpensive gelatin filter would eliminate it without otherwise affecting the operation of the system.

The only physical connection between the subject and the oculometer system is the head restraint. While this represents somewhat of an unnatural constraint on the subject, it is necessary in order to insure that the subject's eye remains within the field of view of the camera. While it is somewhat less than the ideal situation of no restraint, it represents a considerable improvement over earlier restraints such as the "bite-bar".

The oculometer system described in this study recorded data in relation to pupil dilation and eye pointing direction at the rate of one record every thirtieth of a second, on 9-track computer tape. Data concerning the occurrence and duration of blinks was also recorded. From the basic data recorded by the infrared computer based oculometer system, it was possible to plot eye movements of subjects while they looked at various stimulus situations presented to them via a cathode ray display terminal connected to an IBM 1500 CAI system. Pupil dilations and Y-displacements were measured in terms of television scanlines, the distance between two adjacent scanlines being approximately .00072

inches at the face of the vidicon. X-displacements were measured in terms of clock pulses occurring at the rate of one pulse every tenth of a microsecond. The distance between two adjacent clock pulses was approximately .00055 inches at the face of the vidicon.

The accuracy of the infrared computer based oculometer system was assessed in relation to a simulated eye which produced an image on the monitor identical to that of a human eye, but which, unlike the human eye could be made to remain perfectly stationary. The variances of both dilation and Y-displacement recorded by the oculometer system using the simulated eye were 0.00. The variance of the X-displacements was 0.21 clock pulses per second squared. The resolution of the oculometer system was assessed by having a subject visually track a moving target displayed at various locations of the display screen. Based on the observed displacements, it was estimated that the vertical resolution was ±0.16 inches on a display 16 inches from the eye of the subject, or ±0.7 degrees of angle, while the horizontal resolution was ±0.18 inches on a display 16 inches from the eye of the subject or ±0.95 degrees of angle.

Relating the observed capabilities of the oculometer system to the types of conjugate eye movements reported in Chapter 2 of this study, it would appear that the oculometer system would be capable of detecting most small conjugate eye movements which occur during a fixation, since these eye movements normally occur less than ten times per second and consist of displacements of about ½ degree of angle. Since saccades are reported to occur no more frequently than five times per second, it would appear that the oculometer system would be capable of recording a minimum of six readings during even the shortest inter-saccadic

fixation. For longer fixations, even more readings would be recorded. Also, since satisfactory tracking is only possible at speeds below 200 degrees of angle per second, the oculometer system would be capable of recording an eye pointing coordinate at least once for every seven degrees of angular displacement.

It would appear therefore, that the infrared computer based oculometer system reported in this study would be capable of detecting and recording all types of conjugate eye movements.

While for many studies in education and other fields, the sensitivity of the computer based oculometer system described in this study would be sufficient, greater sensitivity in both the horizontal and vertical directions could easily be accomplished. By using a "non-standard" camera unit, scanning rates of more than 1000 lines could be obtained. This would mean that, compared to the 525-line camera used in this study, the vertical sensitivity could be nearly doubled. Also, by using a faster horizontal time base, for example, 20 megahertz instead of 10 megahertz, the horizontal sensitivity could be doubled.

An oculometer system fully synchronized to a single time base and with better horizontal and vertical sensitivity would certainly reduce the error introduced by the equipment. There is however another source of error, namely error due to the subject. Findings presented in Chapter 4 seem to suggest that even though a subject is looking at a target, his eye pointing direction may not be precisely at the target. Ideally, to assess the capability of the oculometer system to measure eye pointing direction, a plastic model of the eye, mounted on a micrometer head should be used. This would permit accurate pointing of the

eye at known target locations, thereby making it possible to assess the capability of the oculometer to measure eye pointing direction without introducing human error. Such a model was reported to have been built at the Massechussets Institute of Technology, however attempts to obtain it have proved fruitless.

One factor which seriously affected the oculometer output was variation in the intensity of the pupil image. As the pupil fixated various coordinate positions of the display screen, the amount of light reflected by the pupil varied sufficiently so that at times, the pupil intensity was as great as the intensity of the corneal reflection. This resulted in the oculometer system recording the presence of a blink even though no blink occurred. In other instances, increased brightness of the pupil was not sufficient to cause the recording of a blink, however it was sufficient to result in an apparent increase in dilation amounting to one or two lines. This could result in an apparent change in eye pointing direction being recorded by the oculometer different from the change that actually occurred. The addition of an automatic intensity control circuit which would sense the video level coming from the camera unit and would control the intensity of the infrared light source making the video level coming from the camera unit constant, would be a relatively simple addition to the system.

The problem of calibration of the oculometer to a particular subject requires that a reference point on the display screen be established and the horizontal and vertical displacement coordinates be noted when the subject is fixating this reference point. In addition, the horizontal and vertical resolutions must be determined in order to establish a correspondence between a given change in displacement bet-

ween the pupil center and the corneal reflection, and the change in display screen coordinates being fixated. Outcomes of this study were based on the assumptions that for displacements of less than 12 degrees [redacted]tionship would be linear. In this study, readings displaced by more than 12 degrees were corrected for non-linearity, the correction factor being determined by the amount by which the displacement exceeded 12 degrees. It appeared however, that for one subject tested in this study, such a correction factor was not appropriate.

In considering the problem of calibration, it was assumed that the characters displayed on the display screen were of uniform size and of uniform spacing. Upon careful examination of the characters actually produced on the display screen, it was noted that characters varied in both size and spacing and that a small amount of non-linearity existed in the columns of the display screen. Perhaps the most pressing need therefore is to conduct further studies into the effects of non-linearity due to large angular displacements, and to establish reliable calibrating procedures that will take non-linearity into account.

Examination of the plots of eye movements presented in chapter 4 reveals that it is rather difficult to distinguish between fixations and saccades. In addition, such plots are further limited in their usefulness since points occurring at precisely the same coordinate location are plotted as a single point. There is therefore a need to develop better methods of analyzing and displaying eye pointing data. Such developments could optionally include analysis of changes in dilation, blinks, and eye fixations and saccades.

Finally, the development of on-line data handling capabilities which could permit subjects to use eye movements to control peripheral

equipment would appear feasible and worthwhile. Such capabilities would permit users, who for various reasons are incapable of eliciting a motor response, to perform motor tasks such as typing by fixating on specified target coordinates.

Finally, it is recommended that further research be carried out in order to assess the magnitude of the error component inherent in the oculometer output. This study has presented a discussion of the error which is internal to the oculometer system. Further studies, repeated over subjects as well as over occasions would permit an assessment of the magnitude of the overall error component in eye movement data and would also permit error variance to be separated into that which may be attributed to the oculometer system and that which may be attributed to the subject. Similar studies, carried out using other oculography systems would also be desirable since it would facilitate the comparison of the performance of various systems of oculography without requiring that two systems be used to record eye movements simultaneously.

REFERENCES

Adler, F. H. & Fliegelman, M. Influence of fixation on the visual acuity. Arch. Ophthalm., 1934, 12, 475-483.

Barlow, H. B. Eye movements during fixation. J. Physiol., 1952, 116-290.

Barnes, J. A. Tactical Utility helicopter information transfer study. USAF Technical Report No. 7-70, Aberdeen Research and Development Center, Aberdeen Proving Ground, Maryland, 1970.

Berlyne, D. E. The influence of complexity and novelty in visual figures on orienting responses. J. Exp. Psychol., 1958, 55, 289-296.

Boersma, F. J., Muir, W., Wilton, K., & Barham, R. Eye movements during embedded-figure tasks. Perceptual and Motor Skills, 1969(a), 28, 271-274.

Boersma, F. J., Muir, W., Wilton, K., & Barham, R. Eye movements during anagram tasks. Perceptual and Motor Skills, 1969(b), 29, 371-374.

Clark, W. R. & Johnson, D. A. Effects of instructional set on pupillary responses during a short-term memory task. J. Exp. Psychol., 1970, 85, 2, 315-317.

Conklin, R. C., Muir, W., & Boersma, F. J. Field dependency - independency and eye-movement patterns. Perceptual and Motor Skills, 1968, 26, 59-65.

Cornsweet, T. N. Determination of the stimuli for involuntary drifts and saccadic eye movements. J. Apt. Soc. Amer., 1956, 46, 987.

Dodge, R. Five types of eye movements in the horizontal meredian of the field of regard. Amer. J. Physiol., 1903, 8, 307-329.

Dodge, R. An experimental study of visual fixation. Psychol. Rev. Monog. Suppl., 1907, 8, No. 4.

Dodge, R. & Cline, T. S. The angle velocity of eye movements. Psychol. Rev., 1901, 8, 145-157.

Doran, J. & Holland, J. G. Eye movements as a function of response contingencies measured by blackout technique. Learning Research and Development Center, University of Pittsburgh, 1969.

Drake, D. M. Perceptual correlates of impulsive and reflective behavior. Developmental Psychology, 1970, 2, 202-214.

Enoch, J. M. Effect of the size of a complex display upon visual search. J. Opt. Soc. Amer., 1959, 49, 280-286.

Erdmann, B. & Dodge, R. Psychologische Untersuchungen ueber das Lesen auf experimenteller Grundloge. Halle: Max Niemeyer, 1898.

Faw, T. T. & Nunnally, J. C. The effects on eye movements of complexity, novelty, and affective tone. Perception and Psychophysics, 1967, 2, 263-267.

Faw, T. T. & Nunnally, S. C. The influence of stimulus complexity, novelty, and affective value on children's visual fixations. Journal of Experimental and Child Psychology, 1968, 6, 141-153.

Feinstein, R. Interactions of the horizontal and vertical eye movement systems. Unpublished Ph.D. thesis, University of Michigan, 1970.

Fleming, M. Eye movement indices of cognitive behavior, A.V. Communication Review, 1969, 17, 4, 383-398.

Gainer, C.A. & Obermayer, R. W. Pilot eye fixations while flying selected maneuvers using two instrument panels. Human Factors, 1964, 6, 485-501.

Gould, J. D. & Schaffer, A. Eye movement patterns during visual information processing. Psychonom. Science, 1965, 3, 317-318.

Gould, J. D. Pattern recognition and eye-movement parameters. Perception and Psychophysics, 1967, 2, 399-407.

Gould, J. D. & Brown, A. Eye-movement parameters and pattern discrimination. Paper presented to Psychonomic Society, Chicago, October 1967.

Gould, J. D. & Schaffer, A. Eye-movement parameters in pattern recognition. J. Exp. Psychol., 1967, 74, 225-229.

Gould, J. D. & Dill, A. B. Eye-movement parameters and pattern discrimination. Perception and Psychophysics, 1969, 6, 311-320.

Gould, J. D. & Peeples, D. R. Eye movements during visual search and discrimination of meaningless symbol and object patterns. J. Exp. Psychol., 1970, 85, 1, 51-55.

Greenberg, D. J. & Weizmann, F. The measurement of visual attention in infants: A comparison of two methodologies. Journal of Experimental Child Psychology, 1971, 11, 234, 243.

Guba, E., Wolf, W., de Groot, S., Knemeyer, M., Van Atta, R., & Light, L. Eye movements and TV viewing in children. Audio-Visual Communication Review, 1964, 12, 386-401.

Guilford, J. P. & Hackman, R. B. Varieties and levels of clearness correlated with eye movements. Amer. J. Psychol., 1936, 48, 371-388.

Haltrecht, E. J. & McCormack, P. D. Monitoring eye movements of slow and fast learners. Psychon. Sci., 1966, 6, 461-462.

Hannah, T. E. & McCormack, P. D. Monitoring eye movements of high and low-anxiety subjects during acquisition of competitive and non-competitive paired-associate lists. Canadian Journal of Psychology, 1968, 22, 105-113.

Hebb, D. O. The organization of behavior. New York: Wiley, 1949.

Helmholtz, H. V. Handbuck der physiologischen optik. Leipzig: Leopold Voss, 1867.

Helmholtz, H. V. Physiological optics. (J.P.C. Southall, Ed.) Vol. 3 New York: Optical Society of America, 1925.

Hess, E. H. Attitude and pupil size. Scientific American, 1965, 212, 46-54.

Hess, E. G. & Polt, J. M. Pupil size as related to interest value of visual stimuli. Science, 1960, 132, 349-350.

Hillsman, M. J., Williams, R. W., & Roe, J. S. The computer-controlled oculometer. A prototype interactive eye movement tracking system. M.I.T. Artificial Intelligence Memo No. 253, Sept., 1970.

Huang, A. T. & Smith, K. U. Binocular vertical eye movements. American Journal of Optometry, 1970, 47, 23-30.

Javal, E. Essai sur la psyiologie de la lecture. Annales D'Oculistique, 1879, 82, 242-253.

Kahneman, D. & Beatty, J. Pupil diameter and load on memory. Science, 1966, 154, 1583-1585.

Kaufman, L. & Richards, W. Spontaneous fixation tendencies for visual forms. Percept. and Psychophys., 1969, 5, 85-88.

Krauskopf, J., Cornsweet, T. N., & Riggs, L.A. Analysis of eye movements during monocular and binocular fixation. J. Opt. Soc. Amer., 1960, 50, 6, 572-578.

Luborsky, L., Blinder, B., & Mackworth, N. Eye fixation and recall of pictures as a function of GSR responsitivity. Perc. and Mot. Skills, 1963, 16, 469-483.

Mackworth, N. H. A stand camera for line-of-sight recording. Perception and Psychophysics, 1967, 2, 119-127.

Mackworth, N. H. & Bruner, J. S. Selecting visual information during recognition by adults and children. Mimeographed Monograph, Harward University Center for Cognitive Studies, 1966.

Mackworth, N. H. & Bruner, J. S. Measuring how adults and chilren search and recognize pictures. Human Development, 1970, 13, 149-177.

Mackworth, N. H. & Morandi, A. J. The gaze selects informative details within pictures. Perception and Psychophysics, 1967, 2, 11, 547-552.

Mason, K. A. & Merchant, J. An investigation of techniques of oculometer target position measurement in real-time displays. Unpublished report. Honeywell Radiation Center, Lexington, Mass., 1969.

Matin, L., Matin, E., & Pearce, D. G. Visual perception of direction when voluntary saccades occur. 1 Relation of visual direction of a fixation target extinguished before a saccade to a flash presented during the saccade. Perception and Psychophysics, 1969, 5, 2, 65-80.

McCormack, P.D. & Clemence, G. D. Monitoring eye movement during paired-associate learning in a retroactive inhibition setting. Canadian Journal of Psychology, 1970, 24, 3, 184-193.

McCormack, P.D., Clemence, G. D. & Moore, T. E. Monitoring eye movements under conditions of associative matching, response production, and stimulus and response production. Canadian Journal of Psychology, 1969, 23, 2, 147-155.

McCormack, P. D., Clemence, G. D., Tymm, W. H., & Malabre, M. A. Monitoring eye movements during PA learning under three display conditions. Psychon. Sci., 1969, 15, 6, 277-278.

McCormack, P. D. & Moore, T. E. Monitoring eye movements during the learning of low-high and high-low meaningfulness paired-associate lists. J. Exp. Psychol., 1969, 79. 18-21.

McCormack, P. D. & Haltrecht, E. J. Monitoring eye movements under two conditions of presentations of paried-associate materials. Canadian Journal of Psychology, 1966, 20, 154-159.

McCormack, P. D., Hannah, T. E., Bradley, W. J. & Moore, T. E. Monitoring eye movements under conditions of high and low intralist response (meaningful) similarity. Psychon. Sci., 1967, 8, 517-518.

McCormack, P. D., Haltrecht, E. J. & Hannah, T. E. Monitoring eye movements during the learning of successive paired - associate lists. J. Verb. Learn. Verb. Behav., 1967, 6, 950-953.

Miles, W. R. The peep-hole method for observing eye movements in reading. J. Genet. Psychol., 1928, 1, 373-374.

Miller, L. K. Eye-movement latency as a function of age, uncertainty, and position in the visual field, Perceptual and Motor Skills, 1969, 28, 631-636.

Milton, J. L. & Wolfe, F. J. Eye fixations of aircraft pilots: VIII. Fixations during zero reader appraches in a jet aircraft. USAF Technical Report No. 52-17, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1952.

Milton, J. L., McIntosh, B. B. & Cole, E. L. Eye fixations of aircraft pilots: IX. Routine maneuvers under day and night conditions using an experimental panel arrangement. USAF Technical Report No. 53-220, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1954.

Milton, J. L., McIntosh, B. B. & Cole, E. L. Eye fixations of aircraft pilots: VI. Fixations during day and night ILAS approaches using an experimental panel arrangement. USAF Technical Report No. 6570, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1951.

Milton, J. L., McIntosh, B. B. & Cole, E. L. Eye fixations of aircraft pilots: VII. Fixations during day and night GCA approaches. USAF Technical Report No. 6709, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1952.

Milton, J. L., Jones, R. E. & Fitts, P. M. Eye fixations of aircraft pilots: II. Frequency, duration and sequence of fixations when flying the USAF instrument low approach system (ILAS). USAF Technical Report No. 5839, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1949.

Milton, J. L., Jones, R. E. & Fitts, P. M. Eye fixations of aircraft pilots. V. Frequency, duration and sequence of fixations when flying selected maneuvers during instrument and visual flight conditions. USAF Technical Report No. 6018, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1950.

Moore, T. E. & McCormack, P. D. Monitoring eye movements while studying the effects of response familiarization on paired-associate learning. Psychon. Sci., 1968, 12, 6, 269-270.

Muir, W. Looking behavior in normal and retarded children during directed search tasks and discrimination learning. Unpublished doctoral dissertation, University of Alberta, 1971.

Neisser, U. Visual Search. Scientific American, 1964, 210, 94-102.

Noton, D. & Stark, L. Scanpaths in eye movements during pattern perception. Science, 1971, 171, 308-311.

Nunnally, J. C., Stevens, D. & Hall, G. Association of neutral objects with rewards: effect on verbal evaluation and eye movements. Journal of Experimental Child Psychology, 1965, 2, 44-57.

O'Brien, K. G., & Boersma, F. J. Eye movements and conservation. Unpublished monograph, University of Alberta, 1970.

Pearce, D. G. & Porter, E. Changes in visual sensitivity associated with voluntary saccades. Psychon. Sci., 1970, 19, 4, 225-227.

Rashbass, C. New method for recording eye movements. J. Opt. Soc. Amer., 1960, 50, 7, 642-644.

Richards, W. & Kaufman, L. "Center- of gravity" gendencies for fixations and flow patterns. Perception and Psychophysics, 1969, 5, 2, 81-84.

Robinson, D. A. The mechanics of human saccadic eye movement. J. Physiol., 1964, 174, 245-264.

Robinson, D. A. The mechanics of human smooth pursuit eye movement. J. Physiol., 1965, 180, 569-591.

Schackwitz, A. Apparat zur Aufzeichnung der Augenbewegungen beim zuzammenhangenden Lesen. Zsch. f. Psychol., 1913, 63, 442-453.

Schroeder, S. R. Selective eye movements to simultaneously presented stimuli during discrimination. Perception and Psychophysics, 1970, 7, 2, 121-123.

Schroeder, S. R. & Holland, J. G. Operant control of eye movements. Journal of Applied Behavioral Analysis, 1968, 1, 161-166.

Smith, K. U., Schremser, R. & Putz, V. Binocular coordination in reading. J. App. Psych., 1971, 55, 3, 251-258.

Spache, G. D. Is this a break-through in reading? The Reading Teacher, 1962, 15, 258-263.

Taylor, S. E. Eye-movement photography with the reading eye. Huntington, N.Y.: Educational Developmental Laboratories, 1959.

Taylor, E. A. Controlled reading. Chicago: University of Chicago Press, 1937.

Teichener, W. H. & Price, L. H. Eye aiming behavior during the solution of visual patterns. J. Psychol., 1966, 62, 33-38.

Tinker, M. A. Apparatus for recording eye movements. Amer. J. Psychol., 1931, 43, 115-127.

Tinker, M. A. Bases for effective reading. Minneapolis: University of Minnesota Press, 1965.

Underwood, B. J. & Schulz, R. W. Meaningfulness and verbal learning. Chicago: Lippincott, 1960.

Volkman, F. C. Vision during voluntary saccadic eye movements. J. Opt. Soc. Amer., 1962, 52, 5, 571-578.

Vurpillot, E. The development of scanning strategies and their relation to visual differentiation. Journal of Experimental Child Psychology, 1968, 6, 632-650.

Webb, W., Matheny, A., & Parson, G. Eye avoidance behavior. Perceptual and Motor Skills, 1963, 16, 341-347.

West, D. C. & Boyce, P. R. The effect of flicker on eye movements. Vision Res., 1968, 8, 171-192.

Westheimer, G. Eye movement responses to a horizontally moving visual stimulus. Archives of Ophthalmology, 1954, 52, 932-941.

Whitteridge, D. Central control of eye movements. Chap. XLIII in J. Field (Ed.), Handbook of Physiology, Sect. 1: Neurophysiology, Vol. 2, Washington, D.C.: Amer. Physiol. Soc., 1960.

Wolf, W., Knemeyer, M., de Groot, S., Tira, D., Light, L., & Gansneder, B. A study of eye movement in television viewing. Ohio State University Columbus, 1970.

Yarbus, A. L. Eye movements and vision. New York: Plenum Press, 1968.

Yewchuk, C. R. Eye movements of normal and educable mentally retarded children during discrimination shift learning. Unpublished doctoral dissertation, University of Alberta, 1972.

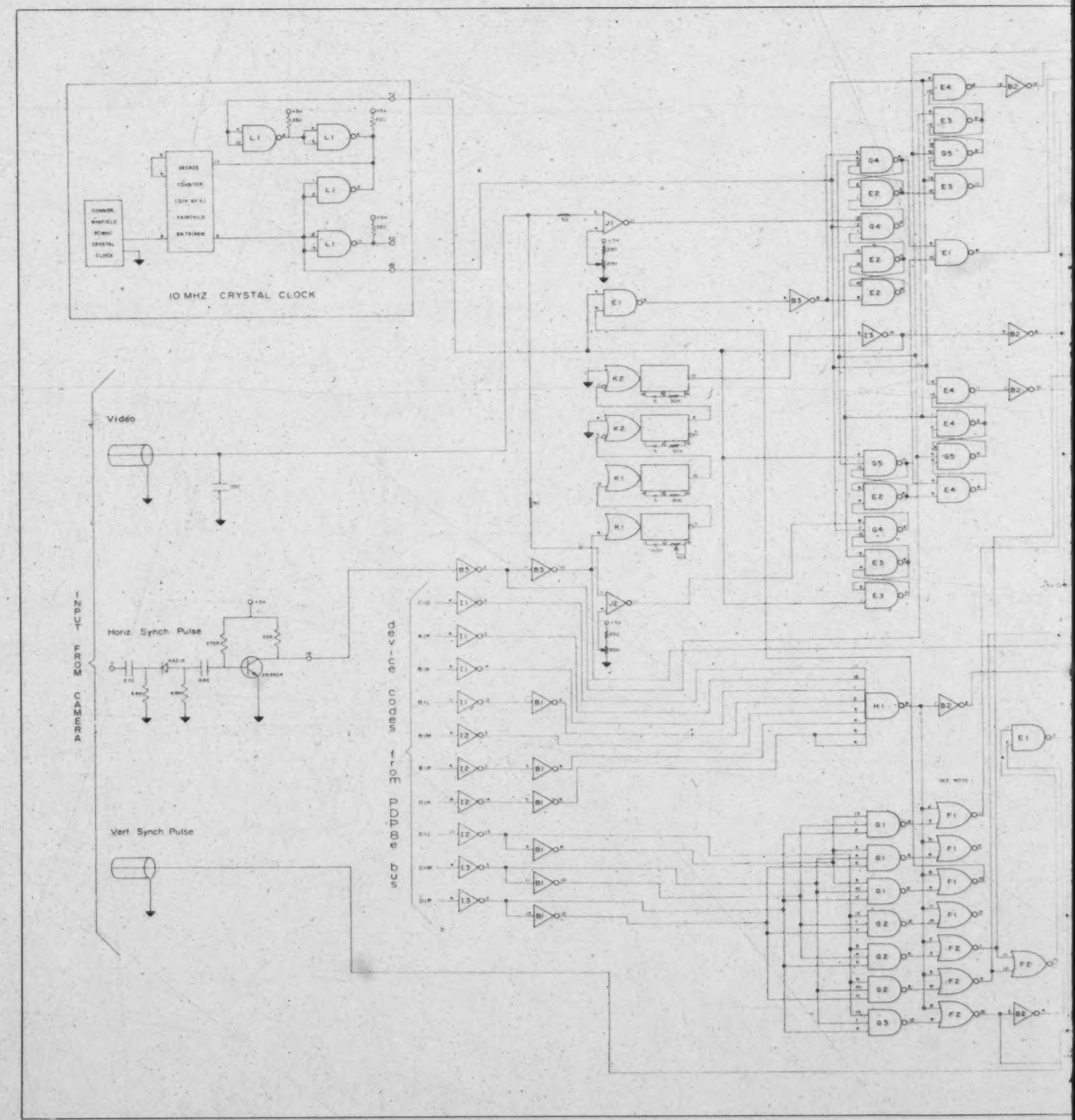
Young, L. R. A sampled data model for eye tracking movements. Sc. D. Thesis, Massachusetts Institute of Technology, 1962.

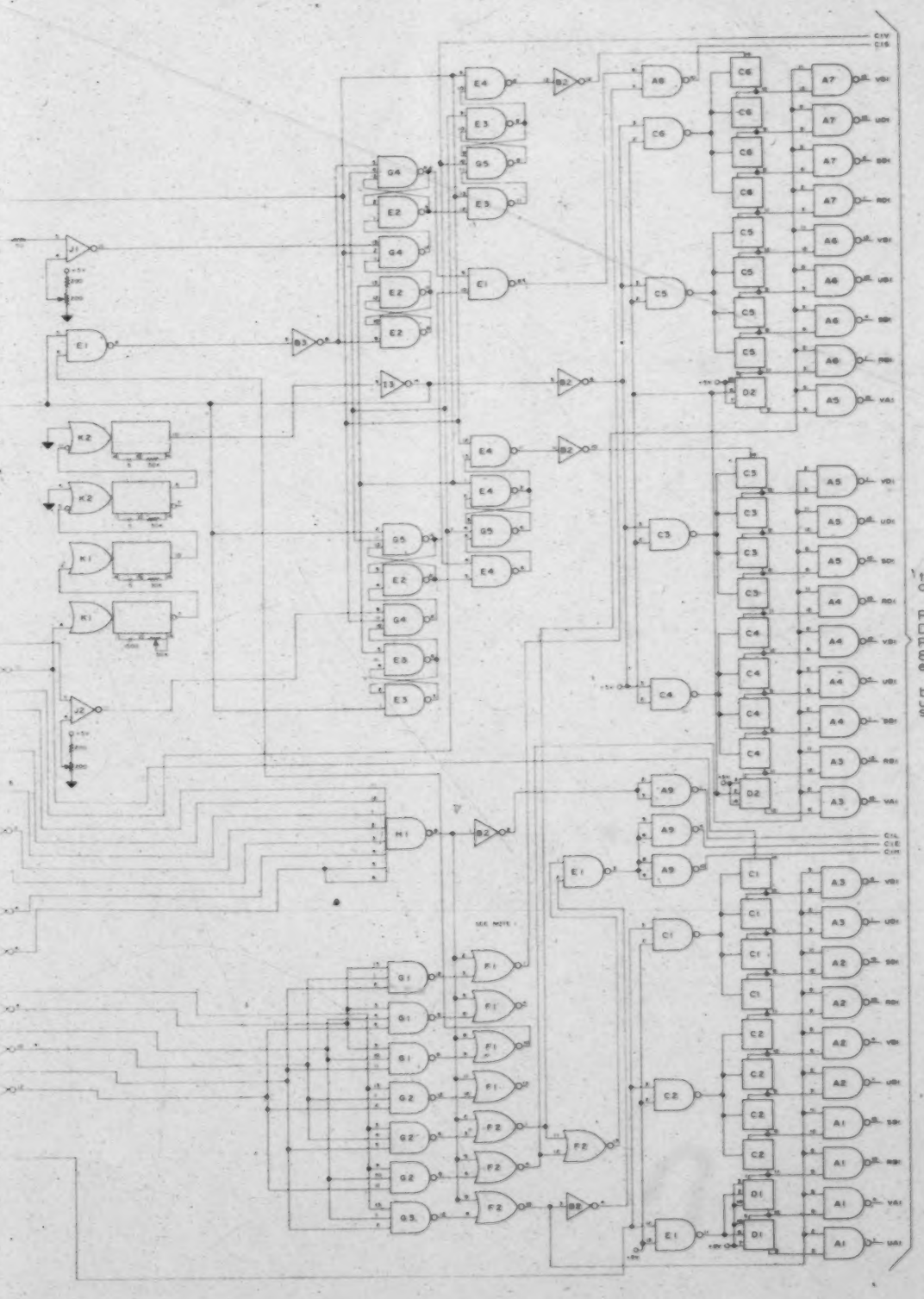
Young, L. R. & Stark, L. A discrete model for eye tracking movements. IEEE Trans. on Military Electronics., MIL-7, 1963, 113-115.

Zinchenko, V. P., Chzhi-Tsin, V. & Tarakanov, V. V. The formation and development of perceptual activity. Soviet Psychol. and Psychiat., 1963, 2, 3-12.

APPENDIX A

1 of


10 MHZ CRYSTAL CLOCK
Vidéo
Horiz Synch Pulse
Vert Synch Pulse
INPUT FROM CAMERA
device codes from PDP8e bus



IC IDENTIFICATIONS

A = 8881	G = 7410
B = 7404	H = 7430
C = 7483	I = 380
D = 7473	J = UA780
E = 7400	K = 9602
F = 7402	L = MC3004P

NOTES

1) CONTROL FUNCTIONS ARE ASSIGNED AS FOLLOWS:

Pin	Octal	Function
F1-1	6041	SKIP ON FLAG
F1-4	6042	SPARE
F1-10	6043	CLEAR FLAG
F1-13	6044	SPARE
F2-1	6045	READ FLIPTIME
F2-4	6046	READ CRTIME
F2-10	6047	READ LINE NO

2) ALL RESISTOR VALUES IN OHMS AND CAPACITOR VALUES IN PICOFARADS

ISSUE	DATE	DWN by	CHK by
2	Aug. 1973	F.P.	M.P.

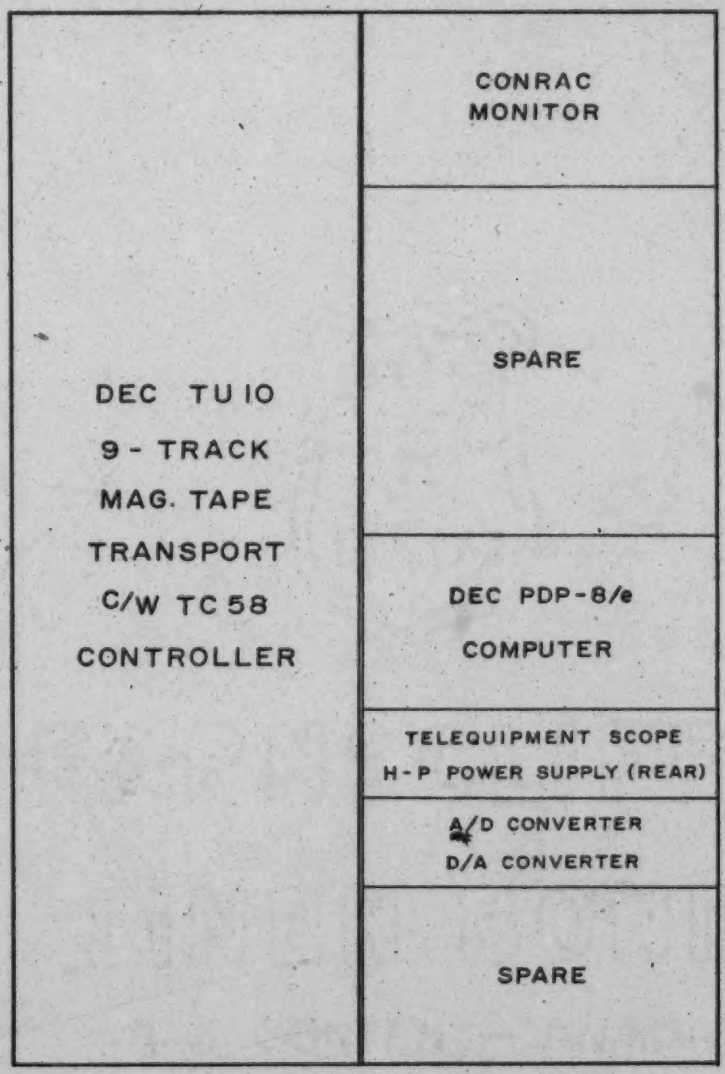
Connected Pin 14 - 13 to Pin F2 - Clock, Pin 5 - E1 and Pin 2 - G5

ISSUE	DATE	DWN by	CHK by
1	April 1973	F.P.	M.P.

COMPUTER - CAMERA INTERFACE UNIT

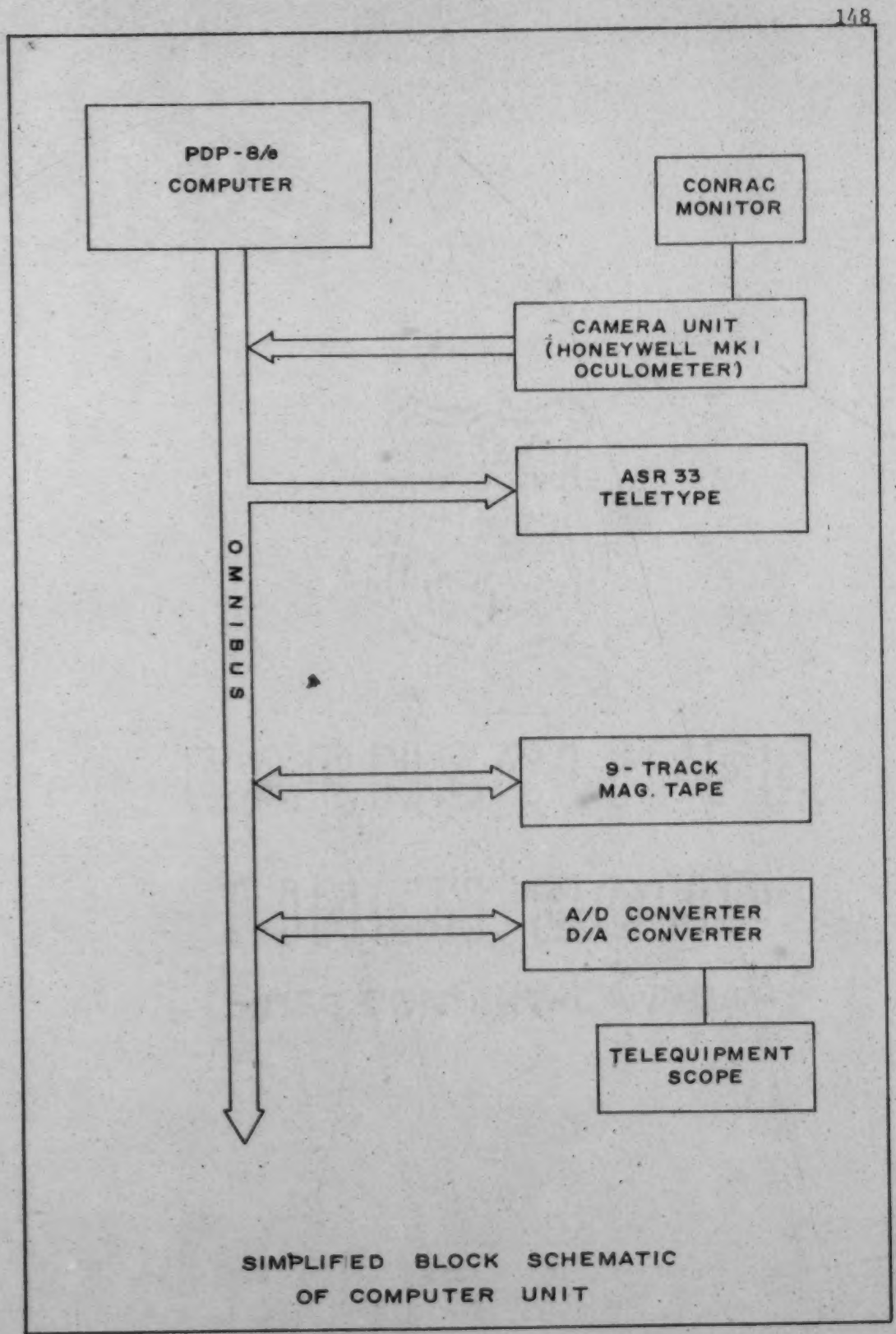
detailed schematic

APPENDIX B



COMPUTER RACK CONFIGURATION

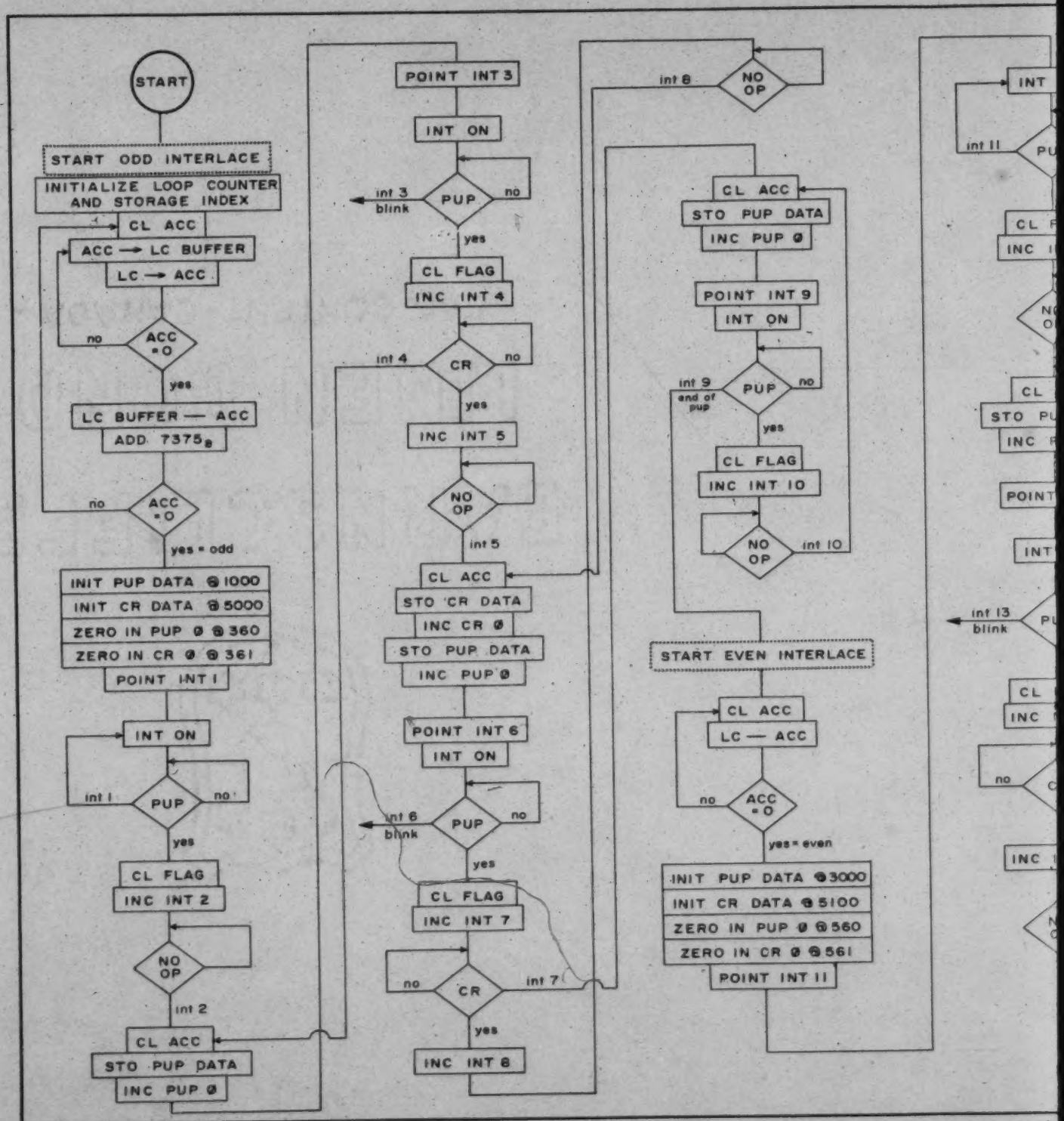
APPENDIX C

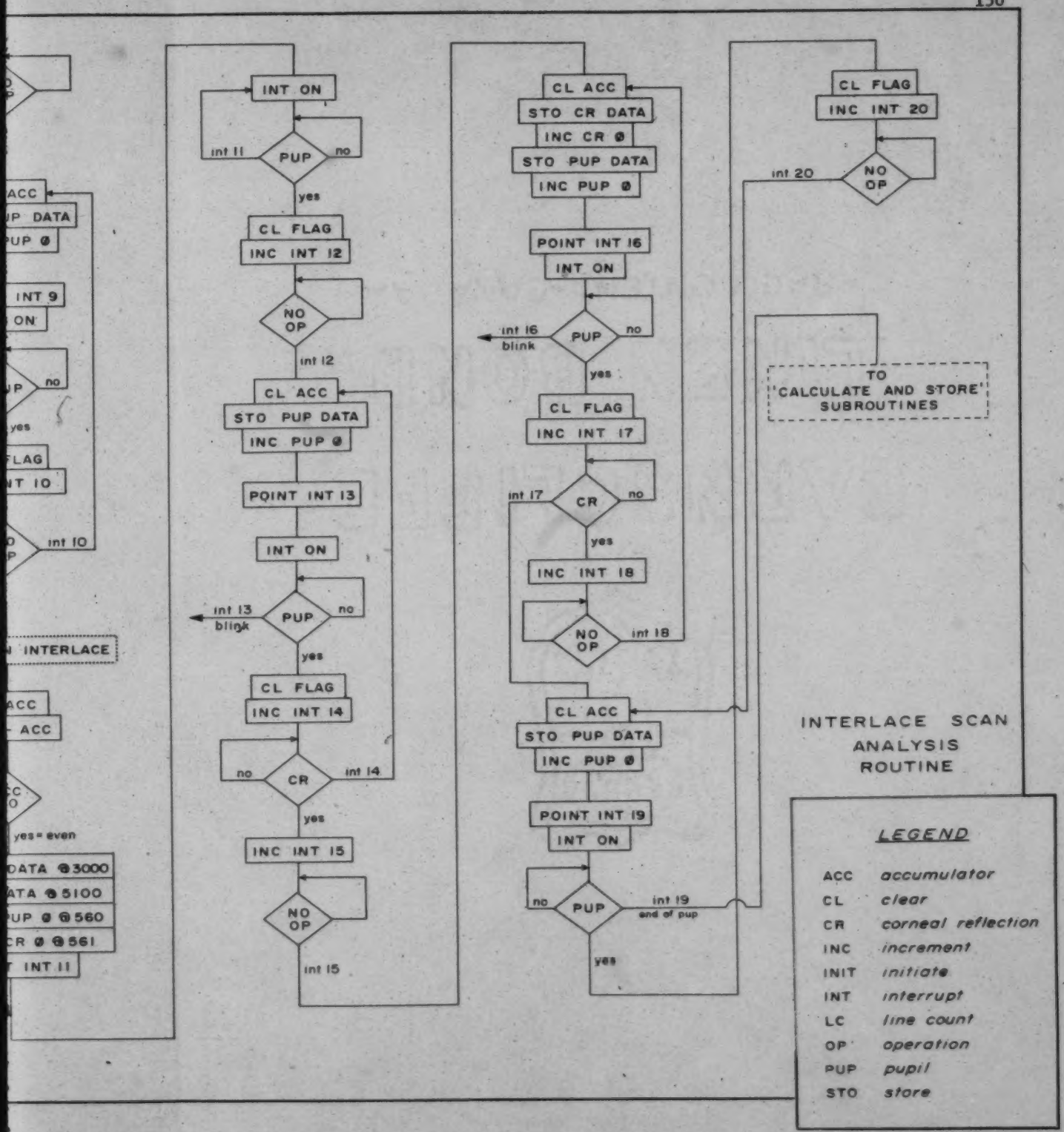


SIMPLIFIED BLOCK SCHEMATIC
OF COMPUTER UNIT

APPENDIX D

1 of


START
START ODD INTERLACE
INITIALIZE LOOP COUNTER AND STORAGE INDEX
CL ACC
ACC → LC BUFFER
LC → ACC
ACC = 0
no
yes
LC BUFFER — ACC
ADD 7375₈
ACC = 0
no
yes = odd
INIT PUP DATA @ 1000
INIT CR DATA @ 5000
ZERO IN PUP Ø @ 360
ZERO IN CR Ø @ 361
POINT INT 1
INT ON
int 1
PUP
no
yes
CL FLAG
INC INT 2
NO OP
int 2
CL ACC
STO PUP DATA
INC PUP Ø
POINT INT 3
INT ON
int 3 blink
PUP
no
yes
CL FLAG
INC INT 4
int 4
CR
no
yes
INC INT 5
NO OP
int 5
CL ACC
STO CR DATA
INC CR Ø
STO PUP DATA
INC PUP Ø
POINT INT 6
INT ON
int 6 blink
PUP
no
yes
CL FLAG
INC INT 7
no
CR
int 7
yes
INC INT 8
int 8
NO OP
CL ACC
STO PUP DATA
INC PUP Ø
POINT INT 9
INT ON
int 9 end of pup
PUP
no
yes
CL FLAG
INC INT 10
NO OP
int 10
START EVEN INTERLACE
CL ACC
LC — ACC
no
ACC = 0
yes = even
INIT PUP DATA @ 3000
INIT CR DATA @ 5100
ZERO IN PUP Ø @ 560
ZERO IN CR Ø @ 561
POINT INT 11
INT
int 11
PU
CL
INC
STO PU
INC
POINT
INT
int 13 blink
PU
CL
INC
no
INC


INT ON
int 11
PUP
no
yes
CL FLAG
INC INT 12
NO OP
int 12
CL ACC
STO PUP DATA
INC PUP Ø
POINT INT 13
INT ON
int 13 blink
PUP
no
yes
CL FLAG
INC INT 14
no
CR
int 14
yes
INC INT 15
NO OP
int 15
CL ACC
STO CR DATA
INC CR Ø
STO PUP DATA
INC PUP Ø
POINT INT 16
INT ON
int 16 blink
PUP
no
yes
CL FLAG
INC INT 17
int 17
CR
no
yes
INC INT 18
NO OP
int 18
CL ACC
STO PUP DATA
INC PUP Ø
POINT INT 19
INT ON
no
PUP
int 19 end of pup
yes
CL FLAG
INC INT 20
int 20
NO OP
TO 'CALCULATE AND STORE' SUBROUTINES
INTERLACE SCAN ANALYSIS ROUTINE
LEGEND
ACC accumulator
CL clear
CR corneal reflection
INC increment
INIT initiate
INT interrupt
LC line count
OP operation
PUP pupil
STO store

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                                1     * THIS PART OF THE PROGRAM SEARCHES FOR THE
                                2     * ODD INTERLACE AND THEN PROCEEDS TO TRACE
                                3     * THE PERIPHERY OF THE PUPIL AND CR FOR THE
                                4     * DURATION OF THE ODD INTERLACE SCAN.
                    00200       5      ORG 200 /BEGIN AT 200
00200  7300                     6     BEGIN CLA+CLL /CLEAR
00201  1422                     7      TAD* 22 /INITIALIZE LOOP
00202  3423                     8      DCA* 23 /COUNTER
00203  1002                     9      TAD 2 /    INITIALIZE AUTOINDEX
00204  3015                    10      DCA 15 /REGISTER FOR DATA STORAGE
00205  7300                    11     SEARCH CLA+CLL
00206  3377                    12      DCA 377 /ZERO IN LC BUFFER
00207  6647                    13      6647 /READ LC
00210  7440                    14      SZA
00211  5206                    15      JMP SEARCH+1 /READ LC BUFFER
00212  1377                   15.5     TAD 377
00213  1376                    16      TAD 376 /ADD CONSTANT
00214  7440                    17      SZA
00215  5205                    18      JMP SEARCH /RETURN, KEEP LOOKING
00216  7300                    19      CLA+CLL
00217  1374                    20      TAD 374 /     INITIALIZE AUTOINDEX
00220  3010                    21      DCA 10 /STORAGE FOR PUPIL DATA
00221  1375                    22      TAD 375
00222  3011                    23      DCA 11 /INITIALIZE STORAGE FOR CR DATA
00223  3360                    24      DCA 360 /INITIALIZE PUPIL DIAMETER COUNTER
00224  3361                    25      DCA 361 /INITIALIZE CR DIAMETER COUNTER
00225  1373                    26      TAD 373 /     POINT
00226  3001                    27      DCA 1 /INTERRUPT 1
00227  6001                    28     I1 ION /INTERRUPT ON
00230  6641                    29      6641 /IS PUPIL HIT?
00231  5230                    30      JMP .-1 /NO - KEEP LOOKING
00232  6643                    31      6643 /YES CLEAR FLAG
00233  2001                    32      ISZ 1 /REPOINT INTERRUPT
00234  7000                    33      NOP /     WAIT
00235  5234                    34      JMP .-1 /FOR INTERRUPT
00236  7300                    35     I24 CLA+CLL
00237  6647                    36      6647 /     READ
00240  3410                    37      DCA* 10 /AND STORE PUPIL LINE NUMBER
00241  6645                    38      6645 /     READ
00242  3410                    39      DCA* 10 /AND STORE PUPIL TIME
00243  2360                    40      ISZ 360 /INCREMENT PUPIL DIAMETER
00244  1372                    41      TAD 372
00245  3001                    42      DCA 1 /POINT INTERRUPT 3
00246  6001                    43      ION /INTERRUPT ON
00247  6641                    44      6641 /IS PUPIL HIT?
00250  5247                    45      JMP .-1 /NO - KEEP LOOKING
00251  6643                    46      6643 /YES CLEAR FLAG
00252  2001                    47      ISZ 1 /REPOINT INTERRUPT
00253  6641                    48      6641 /IS CR HIT?
00254  5253                    49      JMP .-1 /NO, KEEP LOOKING
00255  2001                    50      ISZ 1 /YES, REPOINT INTERRUPT
00256  7000                    51      NOP /     WAIT
00257  5256                    52      JMP .-1 /FOR INTERRUPT
00260  7300                    53     I38 CLA+CLL
00261  6647                    54      6647 /READ AND STORE
```

```
00262  3411          55      DCA* 11 /CR LINE
00263  6646          56      6646 /AND
00264  3411          57      DCA* 11 /CR TIME
00265  2361          58      ISZ 361 /INCREMENT CR DIAMETER
00266  6647          59      6647 /READ AND STORE
00267  3410          60      DCA* 10 /    PUPIL LINE
00270  6645          61      6645 /AND
00271  3410          62      DCA* 10 /PUPIL TIME
00272  2360          63      ISZ 360 /INCREMENT PUPIL DIAMETER
00273  1371          64      TAD 371 /    POINT
00274  3001          65      DCA 1 /INTERRUPT 6
00275  6001          66      ION /INTERRUPT ON
00276  6641          67      6641 /IS PUPIL HIT?
00277  5276          68      JMP *-1 /NO, LOOK AGAIN
00300  6643          69      6643 /YES CLEAR FLAG
00301  2001          70      ISZ 1 /REPOINT INTERRUPT
00302  6641          71      6641 /IS CR HIT?
00303  5302          72      JMP *-1 NO, KEEP LOOKING
00304  2001          73      ISZ 1 /YES REPOINT INTERRUPT
00305  7000          74      NOP /WAIT
00306  5305          75      JMP *-1 /FOR INTERRUPT
00307  7300          76      I710 CLA+CLL
00310  6647          77      6647 /READ AND STORE
00311  3410          78      DCA* 10 /PUPIL LINE
00312  6645          79      6645 /AND
00313  3410          80      DCA* 10 /CR LINE
00314  2360          81      ISZ 360 /INCREMENT PUPIL DIAMETER
00315  1370          82      TAD 370 /REPOINT
00316  3001          83      DCA 1 /INTERRUPT 9
00317  6001          84      ION /INTERRUPT ON
00320  6641          85      6641 /IS PUPIL HIT?
00321  5320          86      JMP *-1 /NO, KEEP LOOKING
00322  6643          87      6643 /YES
00323  2001          88      ISZ 1 /INCREMENT INTERRUPT 10
00324  7000          89      NOP /WAIT
00325  5324          90      JMP *-1 /FOR INTERRUPT
               00360  91      ORG 360
00360  0000          92      0000 /CONTAINS PUPIL DIAMETER ODD
00361  0000          93      0000 /CONTAINS CR DIAMETER ODD
               00370  94      ORG 370
00370  5710          95      5710 /POINT INTERRUPT 9
00371  5705          96      5705 /POINT INTERRUPT 6
00372  5702          97      5702 /POINT INTERRUPT 3
00373  0777          98      0777 /INITIAL ADDRESS FOR PUPIL DATA ODD
00374  4777          99      4777 /INITIAL ADDRESS FOR CR DATA ODD
00375  7375         100      7375 /CONSTANT FOR FINDING ODD INTERLACE
00376  0000         101      0000 /INTERLACE LINECOUNT BUFFER
               00002  102     ORG 2
00002  0377         103      377 /BEGIN STORING DATA HERE
               00022  104     ORG 22
00022  6566         105      6566 /CONTAINS NUMBER OF LOOPS TO BE DONE
00023  6567         106      6567 /USED AS COUNTDOWN FOR NO. OF LOOPS
               00100  107     ORG 100
00100  0227         108      227 /INTERRUPT 1
00101  0236         109      236 /INTERRUPT 2
00102  0321         110      321 /INTERRUPT 3
00103  0236         111      236 /INTERRUPT 4
00104  0260         112      260 /INTERRUPT 5
```

```
     00105  0321           113       321 /INTERRUPT 6
     00106  0307           114       307 /INTERRUPT 7
     00107  0260           115       260 /INTERRUPT 8
     00110  0400           116       400 /INTERRUPT 9
     00111  0307           117       307 /INTERRUPT 10
```

OPERAND CROSS-REFERENCE LISTING

```
     BEGIN     000 00200     6
     I1        000 00227    28
     I24       000 00236    35
     I58       000 00260    53
     I710      000 00307    76
     SEARCH    000 00205    11     000 00211 000 00215
```

```
 ERRORS 0     SCARDS 118     SPRINT 129     SPUNCH 7     STORAGE 3
#20:08.25 1.394 RC=0
#
```

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                                1     * THIS PART OF THE PROGRAM TRACES
                                2     * THE PERIPHERY OF THE PUPIL
                                3     * DURING THE EVEN INTERLACE.
                                4     * TITLE: SEARCHEVEN
                    00400       5      ORG 400 /STARTING ADDRESS IS 400
00400   7300                    6     EVEN CLA+CLL
00401   6647                    7      6647 /READ THE LINE COUNTER
00402   7440                    8      SZA /CHECK FOR 0
00403   5200                    9      JMP EVEN /IF NOT, KEEP LOOKING
00404   7300                   10      CLA+CLL
00405   1374                   11      TAD 574 /INITIALIZE PUPIL DATA
00406   3012                   12      DCA 12 /AT 3000 AND
00407   1375                   13      TAD 575 /CR DATA
00410   3013                   14      DCA 13 /AT 5100
00411   3360                   15      DCA 560 /ZERO PUPIL DIAMETER
00412   3361                   16      DCA 561 /AND CR DIAMETER
00413   1373                   17      TAD 573 /INITIALIZE
00414   3001                   18      DCA 1 /SET INTERRUPT 11
00415   6001                   19     I11 ION /TURN INTERRUPT ON
00416   6641                   20      6641 /IS PUPIL HIT?
00417   5216                   21      JMP .-1 /NO, KEEP LOOKING
00420   6643                   22      6643 /YES, CLEAR FLAG
00421   2001                   23      ISZ 1 /REPOINT INTERRUPT
00422   7000                   24      NOP /WAIT
00423   5222                   25      JMP .-1 /FOR INTERRUPT
00424   7300                   26     I1214 CLA+CLL
00425   6647                   27      6647 /READ AND STORE
00426   3412                   28      DCA* 12 /LINE COUNTER
00427   6645                   29      6645 /AND
00430   3412                   30      DCA* 12 /PUPIL TIME
00431   2360                   31      ISZ 560 /INCREMENT PUPIL DIAMETER
00432   1372                   32      TAD 572 /REPOINT
00433   3001                   33      DCA 1 /INTERRUPT 13
00434   6001                   34      ION /TURN INTERRUPT ON
00435   6641                   35      6641 /IS PUPIL HIT?
00436   5235                   36      JMP .-1 /NO, KEEP LOOKING
00437   6643                   37      6643 /YES, CLEAR FLAG
00440   2001                   38      ISZ 1 /REPOINT INTERRUPT
00441   6641                   39      6641 /IS CR HIT?
00442   5241                   40      JMP .-1 /NO, KEEP LOOKING
00443   2001                   41      ISZ 1 /REPOINT INTERRUPPT
00444   7000                   42      NOP /WAIT
00445   5244                   43      JMP .-1 /FOR INTERRUPT
00446   7300                   44     I1518 CLA+CLL
00447   6647                   45      6647 /READ AND STORE
00450   3413                   46      DCA* 13 /CR LINE
00451   6646                   47      6646 /AND
00452   3413                   48      DCA* 13 /CR TIME
00453   2361                   49      ISZ 561 /INCREMENT CR DIAMETER
00454   6647                   50      6647 /READ AND STORE
00455   3412                   51      DCA* 12 /PUPIL LINE NUMBER
00456   6645                   52      6645 /AND
00457   3412                   53      DCA* 12 /PUPIL TIME
00460   2360                   54      ISZ 560 /INCREMENT PUPIL DIAMETER
00461   1371                   55      TAD 571 /REPOINT
```

```
00462  3001            56      DCA 1 /INTERRUPT 16
00463  6001            57      ION /TURN INTERRUPT ON
00464  6641            58      6641 /IS PUPIL HIT?
00465  5264            59      JMP .-1 /NO, KEEP LOOKING
00466  6643            60      6643 /YES, CLEAR FLAG
00467  2001            61      ISZ 1 /REPOINT INTERRUPT
00470  6641            62      6641 /IS CR HIT?
00471  5270            63      JMP .-1 /NO, KEEP LOOKING
00472  2001            64      ISZ 1 /YES, REPOINT INTERRUPT
00473  7000            65      NOP /WAIT
00474  5273            66      JMP .-1 /FOR INTERRUPT
00475  7300            67     I1720 CLA+CLL
00476  6647            68      6647 /READ AND STORE
00477  3412            69      DCA. 12 /PUPIL LINE NUMBER
00500  6645            70      6645 /AND
00501  3412            71      DCA. 12 /PUPIL TIME
00502  2360            72      ISZ 560 /INCREMENT PUPIL DIAMETER
00503  1370            73      TAD 570 /REPOINT
00504  3001            74      DCA 1 /INTERRUPT 19
00505  6001            75      ION /TURN INTERRUPT ON
00506  6641            76      6641 /IS PUPIL HIT?
00507  5306            77      JMP .-1 /NO, KEEP LOOKING
00510  6643            78      6643 /YES, CLEAR FLAG
00511  2001            79      ISZ 1 /REPOINT INTERRUPT
00512  7000            80      NOP /WAIT
00513  5312            81      JMP .-1 /FOR INTERRUPT
               00560    82      ORG 560
00560  0000            83      0000 /PUPIL DIAMETER EVEN INTERLACE
00561  0000            84      0000 /CR DIAMETER EVEN INTERLACE
               00570    85      ORG 570
00570  5722            86      5722 /POINT INTERRUPT 19
00571  5717            87      5717 /POINT INTERRUPT 16
00572  5714            88      5714 /POINT INTERRUPT 13
00573  5712            89      5712 /POINT INTERRUPT 11
00574  2777            90      2777 /STORAGE LOCATION FOR EVEN PUPIL DATA
00575  5077            91      5077 /STORAGE LOCATION FOR EVEN CR DATA
               00112    92      ORG 112
00112  0415            93      415 /INTERRUPT 11
00113  0424            94      424 /INTERRUPT 12
00114  0321            95      321 /INTERRUPT 13
00115  0424            96      424 /INTERRUPT 14
00116  0446            97      446 /INTERRUPT 15
00117  0321            98      321 /INTERRUPT 16
00120  0475            99      475 /INTERRUPT 17
00121  0446           100      446 /INTERRUPT 18
00122  0514           101      514 /INTERRUPT 19
00123  0475           102      475 /INTERRUPT 20
```

OPERAND CROSS-REFERENCE LISTING

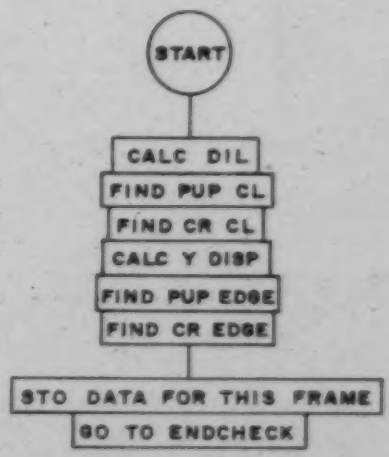
```
EVEN    000 00400     6    000 00403
I11     000 00415    19
I1214   000 00424    26
I1518   000 00446    44
I1720   000 00475    67
```

```
PDP-8 ASSEMBLER
03-12-73  (01-02-70 VERSION)    PAGE 3                          156

 ERRORS 0      SCARDS 102      SPRINT 111      SPUNCH 5      STORAGE 2
#22:36.47 1.307 RC=0
#
```

LEGEND

CALC	calculate
CL	centerline
CR	corneal reflection
CT	centertime
DIL	dilation
DISP	displacement
PUP	pupil
STO	store



CALCULATE & STORE
SUBROUTINE

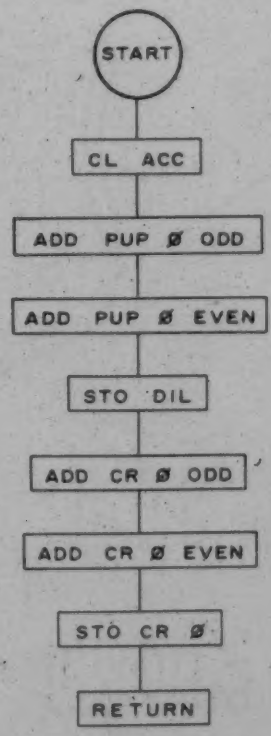
PDP-8 ASSEMBLER

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
00000  0000              1     *TITLE: SUBROUTINES
00001  0001              2     *THIS SERIES OF SUBROUTINES CALCULATES
00002  0002              3     *AND STORES DISPLACEMENT OF CORNEAL
00003  0003              4     *REFLECTION CENTER FROM THE PUPIL
00004  0004              5     *CENTER AND DILATION
00005  0005              6     *IT IS ENTERED VIA INTERRUPT 10 OF
                                 SEARCHEVEN
                  00514   7     ORG 514
00514  4740              8    SUB JMS* 540 /CALCULATES DILATIONS
00515  4741              9     JMS* 541 /FINDS PUPIL CENTERLINE
00516  4742             10     JMS* 542 /FINDS CR CENTERLINE
00517  4743             11     JMS* 543 /FINDS PUPIL CENTERTIME
00520  4744             12     JMS* 544 /FINDS CR CENTERTIME
00521  4745             13     JMS* 545 /CALCULATES X-DISPLACEMENT
00522  7000             14     7000 /NO-OP
00523  4747             15     JMS* 547 /STORES DATA IN CORE 0
00524  5750             16     JMP* 550 /CHECKS TO SEE IF MORE SCANS
                                 NEEDED
                  00540  17     ORG 540
00540  0600             18     600 /LOCATION OF DILATION SUBROUTINE
00541  0613             19     613 /LOCATION OF PUPIL C.L. SUBROUTINE
00542  0652             20     652 /LOCATION OF CR C.L. SUBROUTINE
00543  6510             21     6510 /LOCATION OF Y-DISPLACEMENT
                                 SUBROUTINE
00544  7200             22     7200 /LOCATION OF NEW CR CT SUBROUTINE
00545  6600             23     6600 /LOCATION OF X-DISPLACEMENT
                                 SUBROUTINE
00546  7000             24     7000 /NO-OP
00547  5650             25     5650 /LOCATION OF DATA STORAGE
                                 SUBROUTINE
00550  6560             26     6560 /LOCATION OF END SUBROUTINE
```

OPERAND CROSS-REFERENCE LISTING

```
SUB    000  00514    8
```



DILATIONS
SUBROUTINE

LEGEND

ACC	*accumulator*
CL	*clear*
CR	*corneal reflection*
PUP	*pupil*
STO	*store*

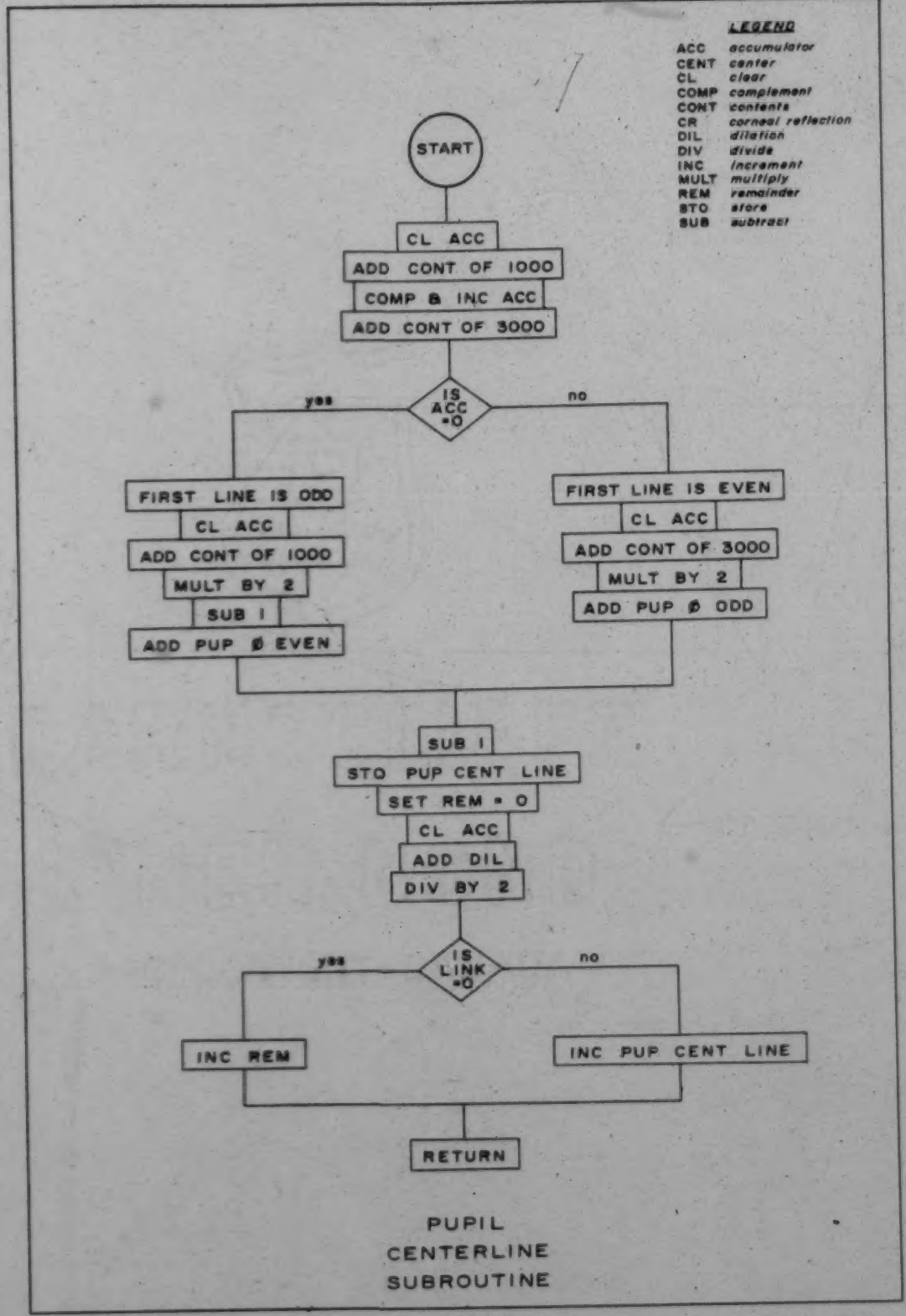
ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                                1     * DIAMETER SUBROUTINES
                                2     * CALCULATE DIAMETERS OF PUPIL
                                3     * AND CORNEAL REFLECTION, GIVEN
                                4     * ODD AND EVEN INTERLACE SCAN DATA
                          00600 5      ORG 600 /STARTING ADDRESS - 600
     00600  7000               6     BEGIN NOP /SR RETURN POINTER
     00601  1124               7      TAD 124 /LOAD PUP DIAM ODD
     00602  1125               8      TAD 125 /ADD PUP DIAM EVEN
     00603  3140               9      DCA 140 /STORE PUP DIAMETER
     00604  1133              10      TAD 133 /LOAD CR DIAM ODD
     00605  1134              11      TAD 134 /ADD CR DIAM EVEN
     00606  3137              12      DCA 137 /STORE CR DIAMETER
     00607  5600              13      JMP* BEGIN /RETURN
```

OPERAND CROSS-REFERENCE LISTING

```
     BEGIN    000 00600     6     000 00607
```

```
 ERRORS 0     SCARDS 13     SPRINT 17     SPUNCH 2     STORAGE 2
#21:31.36 .285 RC=0
#
```

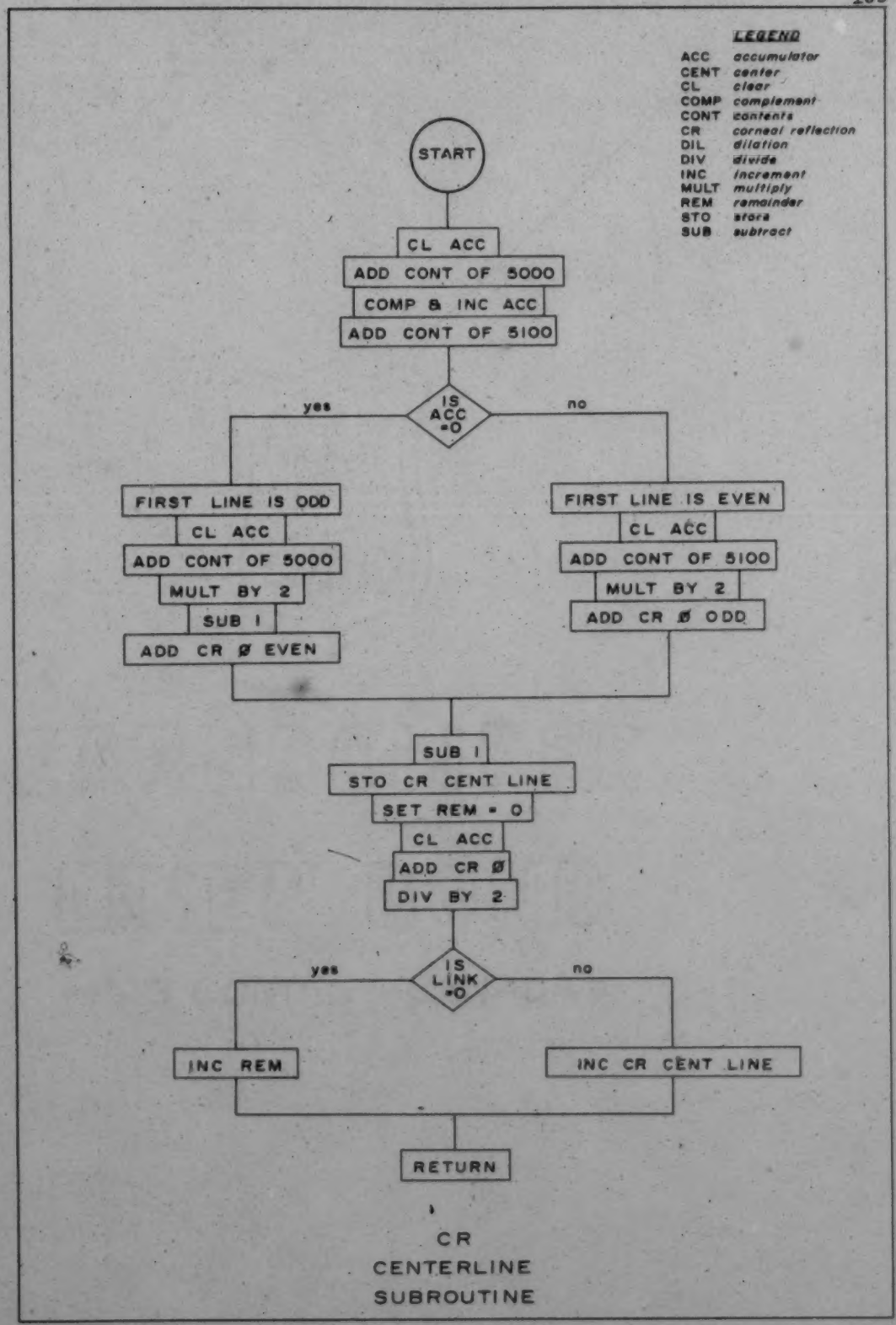


PUPIL
CENTERLINE
SUBROUTINE

PDP-8 ASSEMBLER

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                                1  * TITLE: PUPCEN
                                2  * THIS SUBROUTINE IS CALLED WHEN
                                3  * THE DILATION SUBROUTINE ENDS.
                                4  * THIS SUBROUTINE CALCULATES THE
                                5  * PUPIL CENTERLINE.
                                6  * THE PUPIL CENTERLINE NUMBER IS
                                7  * STORED IN LOCATION 141 WITH THE
                                8  * HALF-LINE REMAINDER IN LOCATION 142
                    00613       9   ORG 613
 00613  0000                    10  PUPCEN 0000 /RETURN ADDRESS
 00614  7300                    11   CLA+CLL
 00615  1526                    12   TAD* 126 /GET LINE 1 ODD
 00616  7041                    13   CIA
 00617  1527                    14   TAD* 127 /GET LINE 1 EVEN
 00620  7440                    15   SZA
 00621  5243                    16   JMP L1E /LINE 1 IS EVEN SO JUMP
 00622  7300                    17   CLA+CLL
 00623  1526                    18   TAD* 126 /LINE 1 IS ODD SO CONTINUE
 00624  7004                    19   RAL /DOUBLE
 00625  1132                    20   TAD 132 /SUBTRACT 1
 00626  1525                    21   TAD* 125 /ADD DILATION
 00627  1132                    22  FIN TAD 132 /SUBTRACT 1
 00630  3141                    23   DCA 141 /STORE PUPIL CENTERLINE
 00631  3142                    24   DCA 142 /AND HALF LINE (141-142)
 00632  7300                    25   CLA+CLL
 00633  1140                    26   TAD 140 /GET PUPIL DILATION
 00634  7010                    27   RAR /DIVIDE BY 2
 00635  7430                    28   SZL
 00636  5241                    29   JMP LK10 /LINK=1, DIAMETER ODD
 00637  2142                    30   ISZ 142 /DIAMETER EVEN
 00640  5613                    31   JMP* PUPCEN /RETURN
 00641  2141                    32  LK10 ISZ 141 /DIAMETER ODD
 00642  5613                    33   JMP* PUPCEN /RETURN
 00643  7300                    34  L1E CLA+CLL
 00644  1527                    35   TAD* 127 /LINE 1 EVEN-CONTINUE
 00645  7004                    36   RAL /DIVIDE LINE 1 EVEN BY 2
 00646  1524                    37   TAD* 124 /ADD PUPIL DIAMETER
 00647  5227                    38   JMP FIN /GO TO STORE
                    00132       39   ORG 132
 00132  7777                    40   7777 /SUBTRACT 1 CONSTANT
OPERAND CROSS-REFERENCE LISTING
```



CR
CENTERLINE
SUBROUTINE

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

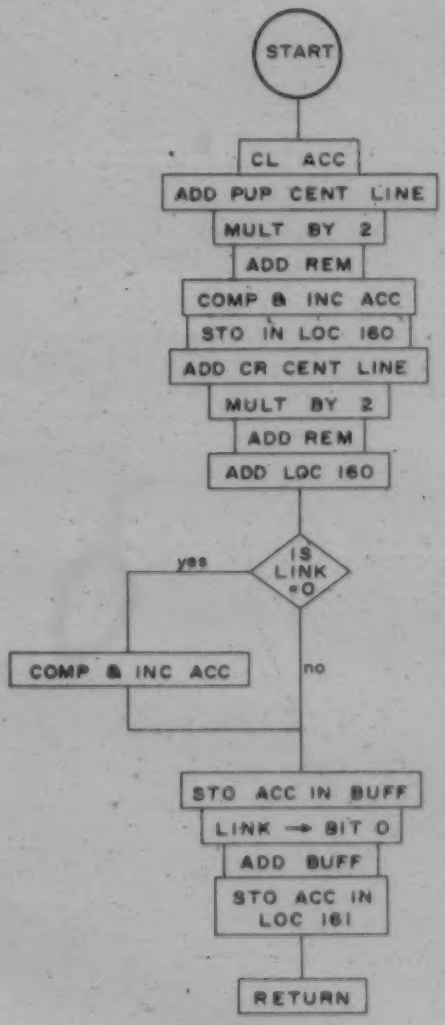
```
                                    1     * TITLE: CRCENT
                                    2     * THIS SUBROUTINE IS CALLED WHEN THE PUPIL
                                    3     * CENTERLINE SUBROUTINE ENDS.
                                    4     * THIS SUBROUTINE CALCULATES THE CR
                                    5     * CENTERLINE.
                                    6     * THE CR CENTERLINE IS STORED IN
                                    7     * LOCATION 145 WITH THE HALF-LINE
                                    8     * REMAINDER IN LOCATION 146.
                          00652     9      ORG 652
00652  0000                        10     CRCENT 0000 /RETURN ADDRESS
00653  7300                        11      CLA+CLL
00654  1535                        12      TAD* 135 /GET LINE 1 ODD
00655  7041                        13      CIA
00656  1536                        14      TAD* 136 /SUBTRACT LINE 1 EVEN
00657  7440                        15      SZA
00660  5302                        16      JMP L1E /LINE 1 IS EVEN-JUMP
00661  7300                        17      CLA+CLL
00662  1535                        18      TAD* 135 /LINE 1 IS ODD-CONTINUE
00663  7004                        19      RAL /DOUBLE IT
00664  1132                        20     FIN TAD 132 /SUBTRACT 1
00665  1534                        21      TAD* 134 /ADD DIAMETER
00666  1132                        22      TAD 132 /SUBTRACT 1
00667  3145                        23      DCA 145 /STORE CR CENTERLINE
00670  3146                        24      DCA 146 /AND HALF-LINE(145&146)
00671  7300                        25      CLA+CLL
00672  1137                        26      TAD 137 /GET CR DIAMETER
00673  7010                        27      RAR /DIVIDE IT BY 2
00674  7430                        28      SZL
00675  5300                        29      JMP LK10 /LINK=1, DIAMETER ODD
00676  2146                        30      ISZ 146 /DIAMETER EVEN
00677  5652                        31      JMP* CRCENT /RETURN
00700  2145                        32     LK10 ISZ 145 /DIAMETER ODD
00701  5652                        33      JMP* CRCENT /RETURN
00702  7300                        34     L1E CLA+CLL
00703  1536                        35      TAD* 136 /LINE 1 EVEN-CONTINUE
00704  7004                        36      RAL /DIVIDE LINE 1 EVEN BY 2
00705  1533                        37      TAD* 133 /ADD CR DIAMETER
00706  5264                        38      JMP FIN /GO TO STORE
                          00132     39      ORG 132
00132  7777                        40      7777 /SUBTRACT 1 CONSTANT
```

OPERAND CROSS-REFERENCE LISTING

```
CRCENT   000 00652   10      000 00677 000 00701
FIN      000 00664   20      000 00706
LK10     000 00700   32      000 00675
L1E      000 00702   34      000 00660
```

ERRORS 0 SCARDS 40 SPRINT 47 SPUNCH 3 STORAGE 2
#22:16.42 .586 RC=0
#

LEGEND	
ACC	accumulator
BUFF	buffer
CENT	center
CL	clear
COMP	complement
CR	corrogal reflection
INC	increment
LOC	location
MULT	multiply
PUP	pupil
REM	remainder
STO	store



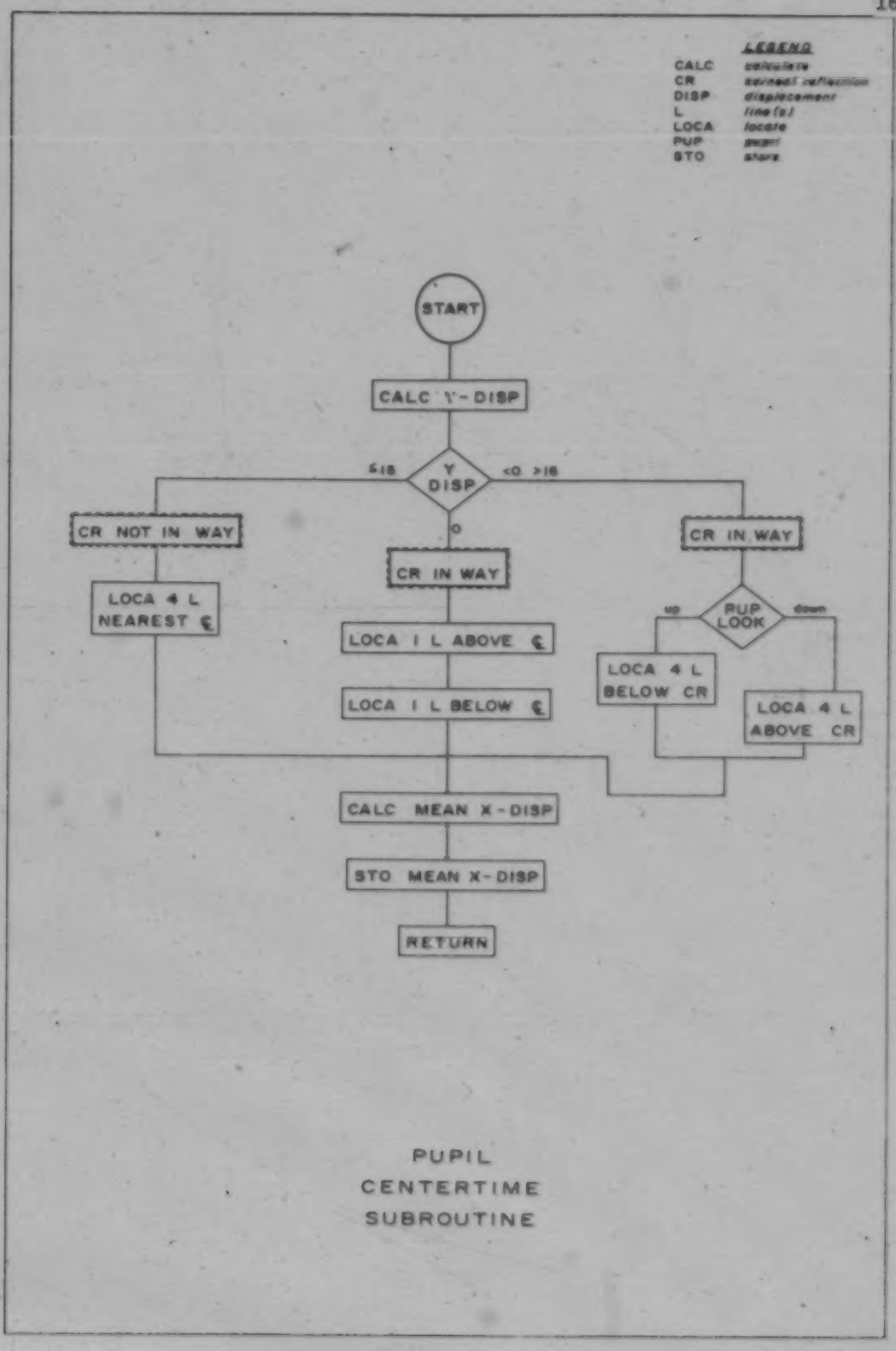
Y-DISPLACEMENT SUBROUTINE

PDP-8 ASSEMBLER

ASSEMBLY LISTING (ALL NUMBERS ARE IN OCTAL)

```
                                1  * TITLE: YDISP
                                2  * THIS SUBROUTINE IS CALLED WHEN THE
                                3  * X-DISPLACEMENT SUBROUTINE ENDS.
                                4  * THIS SUBROUTINE CALCULATES THE
                                5  * Y-DISPLACEMENT BETWEEN THE PUPIL
                                6  * CENTER AND THE CR CENTER AND STORES
                                7  * IT IN LOCATION 161.
                                8  * THE UNITS OF MEASURE ARE HALF-LINES.
                         06540  9   ORG 6504
    06504  7440               10  ZERO SZA /IS ACC 0?
    06505  5326               11   JMP STOR
    06506  7300               12   CLA+CLL
    06507  5326               13   JMP STOR
    06510  0000               14  YDISP 0000 /RETURN ADDRESS
    06511  7300               15   CLA+CLL
    06512  1141               16   TAD 141 /DOUBLE PUPIL
    06513  7004               17   RAL /CENTER
    06514  1142               18   TAD 142 /COMPLEMENT
    06515  7041               19   CIA /AND
    06516  3160               20   DCA 160 /STORE
    06517  1145               21   TAD 145 /DOUBLE
    06520  7004               22   RAL /CR CENTER
    06521  1146               23   TAD 146
    06522  1160               24   TAD 160 /SUBTRACT PUPIL CENTER
    06523  7430               25   SZL
    06524  5304               26   JMP ZERO
    06525  7041               27   CIA /PUT LINK 1
    06526  3333               28  STOR DCA TEMP /IN
    06527  7010               29   RAR /BIT 0 AND
    06530  1333               30   TAD TEMP /STORE IN 161
    06531  3161               31   DCA 161
    06532  5710               32   JMP* YDISP /RETURN
    06533  0000               33  TEMP 0000 /BUFFER
OPERAND CROSS-REFERENCE LISTING

    STOR   000 06526          28   000 06505 000 06507
    TEMP   000 06533          33   000 06526 000 06530
    YDISP  000 06510          14   000 06532
    ZERO   000 06504          10   000 06524
```



PUPIL
CENTERTIME
SUBROUTINE

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                                  200     * TITLE: PCTIME
                                  201     * THIS SUBROUTINE IS CALLED WHEN THE
                                  202     *CR TIME SUBROUTINE ENDS
                                  203     *IT FINDS THE LEFT EDGE OF THE PUPIL
                        07200     204      ORG 7200
07200   0000                      205     START 0000 /RETURN ADDRESS
07201   7300                      206      CLA+CLL
07202   7000                      207      NOP
07203   1140                      208      TAD 140 /DILATION
07204   7012                      209      RTR /TWO RIGHT
07205   7430                      210      SZL
07206   5311                      211      5311 /STORE LINE 1
07207   7004                      212      RAL
07210   1151                      213     A TAD 151 /PUPIL TIME LINE1
07211   3033                      214      DCA 33 /STO 33
07212   1377                      215      TAD 7377 /177=7772
07213   3045                      216      DCA 45
07214   7300                      217      CLA+CLL
07215   1161                      218      TAD 161 /Y LINE DISP
07216   7004                      219      RAL
07217   7100                      220      CLL
07220   7010                      221      RAR
07221   1375                      222      TAD 7375 /7375=7761
07222   7510                      223      SPA
07223   5715                      224      5715 /JMP TO 7400
07224   7300                      225      CLA+CLL
07225   1033                      226      TAD 33
07226   1024                      227      1024
07227   1024                      228      1024 /SUBTRACT 2
07230   3034                      229      DCA 34
07231   1034                      230      TAD 34
07232   0374                      231      AND 7374 /7374=2000
07233   7440                      232      SZA
07234   5302                      233      5302 /JMP B
07235   7300                      234      CLA+CLL
07236   1034                      235      TAD 34
07237   1374                      236      TAD 7374
07240   3035                      237      DCA 35
07241   7300                      238      CLA+CLL
07242   1035                      239      TAD 35
07243   7001                      240      IAC
07244   7001                      241      IAC /ADD
07245   3036                      242      DCA 36
07246   7300                      243      CLA+CLL
07247   1433                      244      TAD* 33
07250   1434                      245      TAD* 34
07251   1435                      246      TAD* 35
07252   1436                      247      TAD* 36
07253   3032                      248      DCA 32
07254   5600                      249      JMP* START /RETURN
                        07302     250      ORG 7302
07302   7300                      251     B CLA+CLL
07303   1034                      252      TAD 34
07304   1372                      253      TAD 7372 /+5
07305   5240                      254      5240 /RETURN
```

```
                    07311   255     ORG 7311
07311  7004                 256     RAL
07312  7001                 257     IAC
07313  5210                 258     5210 /JMP TO A
                    07372   259     ORG 7372
07372  6000                 260     6000
07373  7716                 261     7716
07374  2000                 262     2000
07375  7761                 263     7761
07376  7772                 264     7772
07377  7772                 265     7772
```

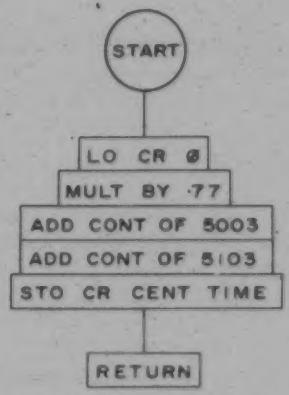
OPERAND CROSS-REFERENCE LISTING

```
A       000 07210   213
B       000 07302   251
START   000 07200   205     000 07254
```

```
 ERRORS 0     SCARDS 66      SPRINT 73      SPUNCH 5      STORAGE 2
#18:45.39 ;918 RC=0
#
```

LEGEND

CENT	center
CONT	contents
CR	corneal reflection
LO	load
MULT	multiply
STO	store



CR
CENTERTIME
SUBROUTINE

```
                                100     *TITLE: CRTIME
                                101     *THIS SUBROUTINE IS CALLED AFTER
                                102     *THE Y DISPLACEMENT IS FOUND
                                103     *IT LOCATES THE LEFT EDGE OF THE
                                104     *CORNEAL REFLECTION
                        06600   105      ORG 6600
06600   0000                    106     START 0000 /RETURN ADDRESS
06601   7300                    107      CLA+CLL
06602   1535                    108      TAD* 135 /LINE 1 ODD
06603   7041                    109      CIA
06604   1536                    110      TAD* 136
06605   7440                    111      SZA
06606   5322                    112      5322 /ODD FIRST
06607   7300                    113      CLA+CLL
06610   1135                    114      TAD 135 /LINE 1 ODD
06611   7001                    115      IAC
06612   3153                    116      DCA 153
06613   5216                    117      5216 /NEXT LINE
06614   0002                    118      0002 /CONSTANT
06615   3153                    119      DCA 153
0661    1153                    120      TAD 153
06617   7001                    121      IAC
06620   7001                    122      IAC /ADD 2
06621   3033                    123      DCA 33
06622   1153                    124      TAD 153 /CR TIME LINE 1
06623   0302                    125      AND 6702 /6702=100
06624   7440                    126      SZA
06625   5313                    127      5313
06626   7300                    128      CLA+CLL
06627   1153                    129      TAD 153
06630   1302                    130      TAD 6702
06631   3034                    131      DCA 34
06632   1034                    132      TAD 34 /NEXT LINE
06633   7001                    133      IAC
06634   7001                    134      IAC /ADD 2
06635   3035                    135      DCA 35 /NEXT LINE
06636   7000                    136      7000
06637   7300                    137      CLA+CLL
06640   1433                    138      TAD* 33
06641   1435                    139      TAD* 35
06642   1434                    140      TAD* 34
06643   3164                    141      DCA 164 / SUM
06644   5600                    142      JMP* START
                        06702   143      ORG 6702
06702   0100                    144      100
                        06722   145      ORG 6722
06722   7300                    146     A CLA+CLL
06723   1136                    147      TAD 136
06724   7001                    148      IAC
06725   5215                    149      5215
                        06713   150      ORG 6713
06713   7300                    151      CLA+CLL
06714   1153                    152      TAD 153
06715   1310                    153      TAD 6710
06716   5231                    154      5231 /RETURN
```

```
                  06710   155       ORG 6710
     06710  7700          156       7700
```

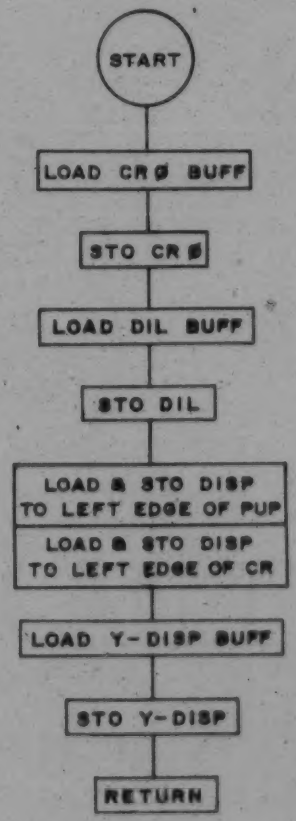
OPERAND CROSS-REFERENCE LISTING

```
     A          000 06722   146
     START      000 06600   106      000 06644
```

```
 ERRORS 0    SCARDS 57      SPRINT 63      SPUNCH 6      STORAGE 2
*18:39.08 .82 RC=0
*
```

LEGEND

BUFF	buffer
DIL	dilation
DISP	displacement
CR	corneal reflection
Ø	diameter
PUP	pupil
STO	store



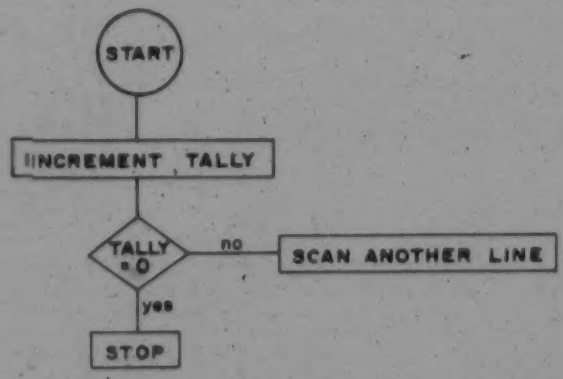
STORE
SUBROUTINE

PDP-8 ASSEMBLER

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                                1    * TITLE: STORE
                                2    * THIS SUBROUTINE BEGINS WHEN THE
                                3    * Y-DISPLACEMENT SUBROUTINE ENDS.
                                4    * THIS SUBROUTINE STORES THE PUPIL
                                5    * DILATION, X-DISPLACEMENT AND
                                6    * Y-DISPLACEMENT IN CONSECUTIVE CORE
                                7    * LOCATIONS OF CORE BLOCK 0.
                         05650  8     ORG 5650
    05650  0000                 9    STORE 0000 /RETURN ADDRESS
    05651  1137                10     TAD 137 /CR DIAM
    05652  4310                11     JMP 5710
    05653  1140                12     TAD 140 /PUP DIL
    05654  4310                13     JMS 5710
    05655  1164                14     TAD 164 /CR EDGE
    05656  4310                15     JMS 5710
    05657  1032                16     TAD 32 /PUP EDGE
    05660  4310                17     JMS 5710
    05661  1161                18     TAD 161 /Y-DISP
    05662  4310                19     JMS 5710
    05663  5650                20     JMP* STORE /RETURN
                         05710  21     ORG 5710
    05710  0000                22    STSR 0000 /RETURN ADDRESS
    05711  6201                23     CDF 0 /DATA FIELD 0
    05712  3415                24     DCA* 15
    05713  6211                25     6211 /DATA FIELD 1
    05714  5710                26     JMP* STSR /RETURN
                         00015  27     ORG 15
    00015  0377                28     377
OPERAND CROSS-REFERENCE LISTING

    STORE       000 05650    9    000 05663
    STSR        000 05710   22    000 05714
```



ENDCHECK
SUBROUTINE

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                                1     * THIS ROUTINE IS ENTERED WHEN THE
                                2     * STORE SUBROUTINE ENDS.
                                3     * THIS ROUTINE DETERMINES WHETHER THE
                                4     * SPECIFIED NUMBER OF 1/30 SECOND
                                5     * LOOPS HAVE BEEN STORED.
                                6     * THE NUMBER OF LOOPS DESIRED IS
                                7     * ENTERED IN LOCATION 6566.
                                8     * WHEN THE SPECIFIED NUMBER OF LOOPS
                                9     * IS COMPLETED, THE PROGRAM HALTS
                               10     * AND WAITS TO BE UNLOADED BY MEANS
                               11     * OF SOME OUTPUT DEVICE.
                     06560     12      ORG 6560
     06560  7300               13     LOOPS CLA+CLL
     06561  2367               14      ISZ 6567
     06562  5421               15      JMP* 21
     06563  7402               16      HLT /STOP
                     06566     17      ORG 6566
     06566  7000               18      7000 /1000 OCTAL LOOPS
                     00021     19      ORG 21
     00021  0205               20      205 /STARTING ADDRESS FOR SEARCHODD.
```

OPERAND CROSS-REFERENCE LISTING

```
     LOOPS .   000 06560    13
```

```
 ERRORS 0     SCARDS 20      SPRINT 24      SPUNCH 4      STORAGE 2
*23:23.06 .335 RC=0
@
```

BLINK
SUBROUTINE

ASSEMBLY LISTING (ALL NUMBERS ARE OCTAL)

```
                                1     * THIS ROUTINE PLACES A 7777 IN THE
                                2     * OUTPUT OF A SEARCH THAT HAS ENCOUNTERED
                                3     * A BLINK.
                                4     * IT THEN RETURNS TO SEARCH TO LOOK FOR
                                5     * THE NEXT FRAME.
                     00321      6      ORG 321
     00321  7300                7     BLINK CLA+CLL
     00322  1024                8      TAD 24 /CORE 24 CONTAINS 7777
     00323  3156                9      DCA 156 /PUT 7777 IN 156 X
     00324  1024               10      TAD 24
     00325  3161               11      DCA 161 /PUT 7777 IN 161 Y
     00326  5762               12      JMP* 362 /362 STORES THE BLINK DATA
                     00362      13      ORG 362
     00362  0523               14      523 /523 POINTS TO STORE ROUTINE
                     00024      15      ORG 24
     00024  7777               16      7777 /BLINK DESIGNATION
```

OPERAND CROSS-REFERENCE LISTING

```
     BLINK    000 00321     7
```

```
 ERRORS 0     SCARDS 16      SPRINT 20      SPUNCH 4      STORAGE 2
#20:25.17 .3 RC=0
#
```